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FUEL GELLING FOR BALLISTIC PROTECTION OF AIRCRAFT FUEL TANKS (U)

By

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A. R. Schleicher

June 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-310(T)

THE WESTERN COMPANY

RESEARCH DIVISION

RICHARDSON, TEXAS

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(U) This report has been prepared by the Western Company, Research Division, under the terms of Contract DA 44-177-AMC-310(T). It consists of a study of different methods in which rapid chemical gelling of fuel is utilized for decreasing the vulnerability of Army aircraft fuel systems under combat conditions.

(U) The results of this study indicate several methods of utilizing rapid fuel gelling for protection against caliber .50 and 20mm ammunition; however, due to their weight and complexity, the systems investigated do not appear to be feasible for use with aircraft fuel systems.

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FUEL GELLING FOR BALLISTIC PROTECTION OF AIRCRAFT FUEL TANKS (U)

Final Report

by

W. G. Setser and A. R. Schleicher

Prepared by

The Western Company

for

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

(U) SUMMARY

Fuel gels formed in situ, preformed gels, and foaming polymers have been investigated to determine their feasibility as self-sealing materials for the protection of aircraft fuel systems. Candidates representing each type of material were evaluated with laboratory and small-scale (9 mm) ballistic tests. Feasibility was determined for the most successful materials on the basis of their ability to seal the holes created by 20 mm projectiles.

Two materials were developed which are feasible for fuel tank sealing. When used in compartmented fuel tanks, they are capable of restricting the amount of fuel lost as the result of hits by 20 mm projectiles.

(U) FOREWORD

This study was initiated in June 1965. Two extensions to the contract were requested; each was 2 months long, and the work was completed in October 1966. The research was performed by W. G. Setser and A. R. Schleicher with the assistance of R. G. Kannenberg during the 20 mm phase of the study.

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(U) INTRODUCTION

BACKGROUND

Slow-flying aircraft operating at low altitudes are vulnerable to small arms ground fire. One of the principal areas of vulnerability has been the aircraft's fuel system. The current solution to such vulnerability employs self-sealing materials in which no significant change in basic design has occurred in years. Although self-sealing materials presently in use are partially effective against some types of ballistics impacts, they do not provide complete protection of the aircraft fuel against loss or ignition.

Recent developments in the field of gel technology have indicated the feasibility of utilizing rapid fuel gelation as a means of protecting aircraft fuel systems against small arms projectiles. Data obtained prior to the issuance of the subject contract also established that gels possessing certain rheological properties, called shear thickening, and rapid foaming reactions possess the capabilities for sealing holes created by small arms projectiles.

PROBLEM

Hits by small arms ground fire occurring on aircraft fuel systems present an extensive hazard to the aircraft and crew from two sources.

1. Unconfined fuel vapors may ignite on contact with hot engine parts or other ignition sources resulting in in-flight fire and eventual crash.

2. Loss of fuel may result in engine fuel starvation, loss of power, and eventual crash.

The prevention or reduction of fuel loss through the use of self-sealing materials increases the survivability of both the aircraft and the crew.

The action of a self-sealing material is to replace the portion of the fuel tank wall that has been deformed or carried away by projectile impact. In order to make and maintain a seal against the pressure caused by a head of fuel, energy is required. Three types of energy that can be utilized for this purpose are:

1. Energy of position - gravity causes the sealant to move over the hole caused by projectile impact.

2. Energy transferred from the projectile to the sealant at impact - rubbers react in this way.

3. Chemical energy - sealing is caused by the formation of a new material such as a gel or a foam.

Complete and rapid sealing is desirable.

The fuel tank seal, once formed, must be strong enough to withstand the shocks and vibrations occurring during flight operations. These can be severe and can include a second projectile impact, fuel sloshing during maneuvering, and landing shock.

Although sealing capability is the principal consideration in evaluating the capability of a fuel tank sealing material, a number of secondary considerations are important. These include but are not limited to:

1. Weight of the self-sealing fuel tank that utilizes the sealing material.
2. Temperature of the sealing chemicals.
3. Flexibility of the self-sealing material to allow easy installation and removal from the fuel tank cavity.
4. Toxicity of the sealing chemicals.

OBJECTIVE

The objective of this study is to perform a feasibility study of different methods which utilize rapid chemical gelling of fuel for decreasing the vulnerability of Army aircraft fuel under combat conditions.

APPROACH

Three classes of self-sealing materials have been evaluated in this research program:

1. Rapid fuel gelling materials.
2. Preformed gels.
3. Rapid foaming materials.

Each class of materials represents several fuel tank sealant candidates.

To facilitate the consideration of the many sealant candidates, the problem was divided into the following categories:

1. Small-scale laboratory and field testing.

2. Large-scale ballistics testing.

The purpose of the first phase of the program was to narrow the number of candidates down to the most promising. The purpose of the second phase of the program was to conduct realistic testing that can establish whether or not a given sealing system is feasible. Large-scale testing is performed primarily with 20 mm ammunition.

The feasibility of the sealing systems tested with 20 mm projectiles is then determined both from the point of view of the test data and with respect to the requirements necessary to include these sealing systems in an operational fuel cell design. Recommendations regarding the further development of the most satisfactory sealing systems are made.

(C) DEVELOPMENT OF THE PROBLEM (U)

(U) Current self-sealing materials have not been totally successful in removing the threat to aircraft posed by small caliber ground fire. The extent of the threat and the capabilities and characteristics of modern fuel tank sealing materials are discussed in the following paragraphs.

(C) The principal threat to slow aircraft operating at low altitude in a limited war situation has been the 7.62 mm projectile fired either from rifle or machine gun. The incidence of larger caliber hits has been very low.

(C) The pilot, engine, fuel system, and hydraulic system of a helicopter are the principal vulnerable components to small arms fire. That the largest single cause of helicopter loss has been reported to be fire indicates the contribution of the fuel tank to the total vulnerability.

(C) Under current limited war conditions, 1 out of every 15 helicopters is downed, for a kill probability of 0.067. A perfectly functioning self-sealing tank is invulnerable. Assuming, for example, that an invulnerable fuel tank reduces the vulnerability of the aircraft by 20 percent, then the kill probability has been reduced to 0.053, or 1 aircraft destroyed out of every 19 hit. This is a considerable reduction in vulnerability.

(U) Although not totally effective, the current state of the art in self-sealing fuel tanks does afford some reduction in vulnerability. However, no new self-sealing techniques have been developed for several years.

(U) Traditionally, the approach has been to line the fuel cells with several layers of rubber-like material. The layer in contact with the fuel is fuel resistant. Between the fuel resistant layer and the aircraft fuel cavity are one or more layers of material designed to provide a measure of puncture sealing. The material may act passively as a puncture size limiter or actively as a sealer, or both.

(U) Puncture-limiting materials compress or deflect during passage of a projectile, then spring back to give an opening smaller than the projectile. Puncture-limiting materials have been fairly effective for restricting the size of punctures made by projectiles with a dimension of less than 1/2 inch. Puncture-limiting materials alone are capable of effective sealing of small punctures if the limiting material is thick enough.

(U) Most of the active sealing systems which have been used on operational aircraft employ materials which swell in contact with fuel. When the fuel-proof layer of the sealing system is ruptured, leaking fuel causes the active sealing layers to swell. The possible effectiveness of the fuel-swelling sealants depends on the amount of swelling the material exhibits compared to the size hole to be sealed.

(U) Systems other than the traditional swellable rubber liner may prove to be promising fuel tank sealing materials. These other systems include chemically formed seals and materials which form seals when coagulated by fuel.

(U) Several approaches have been tried for chemically forming seals in punctured fuel tanks. One method has been to use multiwall structures having the interwall spaces filled with chemicals which form a seal upon activation. Two reactants may be provided in the walls or one in the wall and another or a catalyst in the fuel. Various ingenious types of encapsulation and containment have been employed. These techniques have also been tested to provide protection for space vehicles against puncture by hypervelocity micrometeorites. Typical chemical systems which have been tried include catalyzed polymerization of silicone rubber, polyurethane foam formation, and reactions of the amine-isocyanate type. Temperature variations are an inherent problem in chemical sealing techniques. Reactions which seal effectively at -50^{0}F may be explosively fast at room temperature, and, conversely, systems which are fast at room temperature may be intolerably slow at temperatures around -50^{0}F.

(U) Coagulating materials have been used in conjunction with various supporting materials. The coagulating chemical is contained in a double wall. The interwall space may be filled with fibrous materials impregnated with the coagulating substance. Since the coagulating agent would have little tendency to fill a breach that is leaking fuel, the walls or fibrous matting must serve as effective puncture limiters.

(U) The current state of the art in self-sealing fuel tanks is reflected by the applicable military specifications.

(U) The rubber laminate systems are the only ones which have been accepted for widespread aircraft use. These materials, then, serve as the standard of comparison for new systems. Materials currently available meet the military requirement of making a damp seal in 2 minutes at room temperature and in 4 minutes at -40^{0}F. The best currently available materials are capable of sealing fully tumbled entry and exit holes of 50-caliber projectiles and untumbled entry holes of 20 mm projectiles. A typical quality system may utilize a lining of 0.22-inch thickness. The weight of the sealing system is 1.15 pounds per square foot. With special backing materials, lower weights may be achieved. On late model aircraft, such as the A7A, the self-sealing fuel bag weighs 0.87 pound per square foot. Performance of current systems is predicated on no material's being removed from the puncture by a projectile. The wound may have a well-aligned butt closure with essentially no gap in the closure. Sealing is expected to take place only over gaps of about 1/32 inch.

(U) A chief virtue of the rubber laminate sealing system is simplicity with implied reliability. The system also lends itself to a wide variety of airframe structures.

(U) Chemical and coagulating systems are both still in the experimental stage. The techniques used for sealing against micrometeorites do not appear to be directly transferrable to use against larger projectiles, e.g., 20 mm ammunition. Fallacious analogies may be drawn due to comparing small, hypervelocity projectiles with large, slow projectiles solely on the basis of kinetic energy. The mechanism of puncture and the time rate of momentum transfer must also have a controlling effect on the damage produced. Aside from temperature effects, chemical sealing presents problems due to the complexity of the sealing system compared to rubber laminates. Coagulants are more desirable than chemical systems on this point. Both chemical and coagulant systems require multiwall structures to contain the sealant and to limit the extent of the puncture. From this requirement alone, the chemical and coagulant systems are at a weight disadvantage when compared with rubber laminates. This disadvantage may be overcome, however, if chemical or coagulant systems can offer marked performance improvement over laminates. A system that could seal tumbled entry and exit holes of 20 mm projectiles would represent valuable and useful advances over the current state of the art in self-sealing fuel tanks.

(U) FUEL GELATION AS A MEANS OF SEALING FUEL TANKS

Fuel gelation may be utilized to seal fuel tanks damaged by small arms projectiles in several ways. The gelling chemicals may be stored separately in the fuel tank walls, or one agent may be stored in the walls and one may be dissolved in the fuel. The gelling agents are brought together as the result of projectile penetration.

Fuel gelling materials may also be used as sealants in compartmented tanks. Gelling agents are injected into the compartment that has been breached by a projectile, gelling the fuel in this compartment and preventing continued loss of fuel. Two gelling agents may be injected together, or one gelling agent may be injected and one may be dissolved in the fuel. The injection of the gelling agents may be initiated by impact and fire detection devices.

The laboratory and small-scale ballistics testing of rapid fuel gelation reactions as the means of sealing holes is discussed in general terms in the following paragraphs. A detailed tabulation of experimental data is included in Appendix I.

MULTIWALL FUEL TANKS

To evaluate the tank sealing capability of rapid fuel gelation reactions, a simulated fuel tank was constructed. This apparatus is shown schematically in Figure 1.

The simulated fuel tank apparatus permitted variance of the following factors:

1. The simulated tank could be either two-walled or three-walled.
2. The quantity of gelling agents between the walls would be varied from 1/4 inch to 1 inch by changing spacers.
3. The size of the hole to be sealed could be varied from 1/2 inch to 2 inches.
4. The head of fuel above the hole could be increased to any height up to 3 feet.
5. The gelling agent contained between the walls could be pressurized to move it more rapidly over the hole.

The hole was created by the rapid withdrawal of the spring-loaded plug. Sealing capability was evaluated after reviewing motion picture films taken during each experiment.

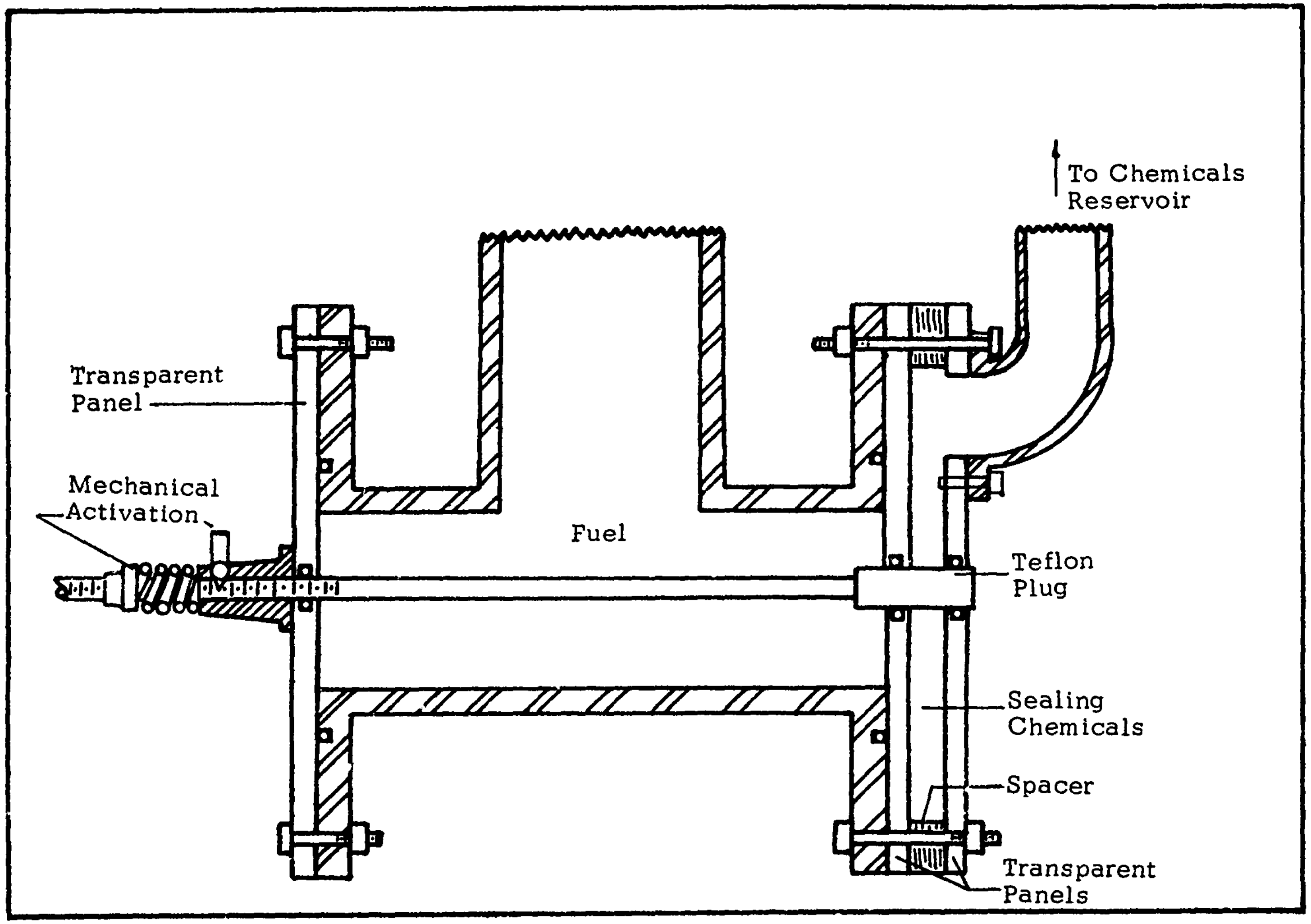

Figure 1. (U) Simulated Fuel Tank.

Chemical gelling systems tested in the simulated fuel tank apparatus were primarily of the soap type. Soap gels are formed when a solution of either sodium or potassium hydroxide (other alkaline chemicals may be used as well) is brought in contact with a fatty acid dissolved in a hydrocarbon liquid. A large number of commerical fatty acids had been evaluated prior to the period covered in this report to determine which would, at low concentrations, rapidly gel hydrocarbon fuels into solid-like materials.

The mixture of the fatty acids

60 volume percent Century 1475 * and
40 volume percent Acentol **

in total concentration of less than 5 percent is capable of gelling hydrocarbon fuels in less than 1 second.

Satisfactory sealing action was not obtained using the simulated fuel tank apparatus in the manner described. Two problems were encountered:

1. The gelling agents could not be satisfactorily blended in the area of the hole to react and form a seal.

2. The gelling agents could not be retained in the area of the hole long enough to react and form a seal.

In order to make use of the energy of projectile impact to blend the gelling agents, small-scale live ammunition testing was initiated. Experiments were performed in which metal, 5-gallon, multiwall fuel containers were made the targets for 9 mm projectiles. An experiment is schematically represented in Figure 2.

In these tests, one entrance hole seal was obtained against the pressure created by a 1-foot head of fuel. Improved blending was achieved as the result of projectile penetration.

The experimental results obtained from simulated fuel tank and small-scale live ammunition tests have indicated that gels formed from gelling agents contained between fuel tank walls and activated as the result of projectile penetration do not form reliable seals.

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*Product of the Harchem Division of Wallace & Tiernan
**Product of the Arizona Chemical Company

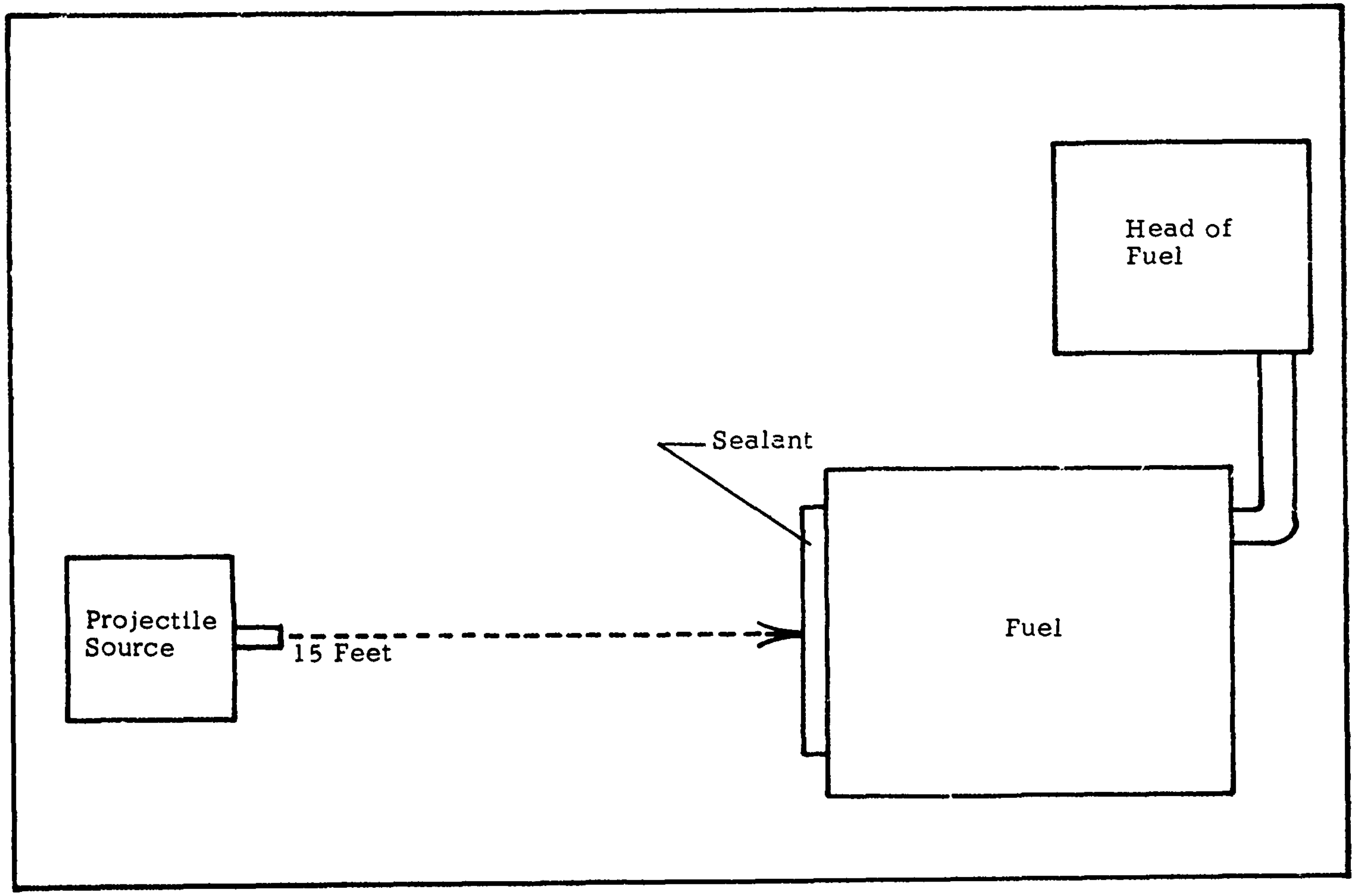


Figure 2. (U) Experimental Setup for 9 mm Ballistics Test on Multiwall Tank.

COMPARTMENTED FUEL TANKS

In order to evaluate the sealing capability of rapid fuel gelation reactions in compartmented tanks, the simulated fuel tank apparatus was modified. Facilities were added for injecting one or two gelling agents into the fuel compartment of the tank just following activation of the tank plug. The modified simulated fuel tank is shown schematically in Figure 3.

As with the multiwall tank experiments, fuel gelation was accomplished with a caustic solution and the following mixture of fatty acids:

60 volume percent Century 1475

40 volume percent Acentol.

The gelling agents were injected into the fuel tank at a pressure of 120 psi. Two to four volume percent (100-200cc) of combined fatty acids and caustic gelling agents were injected for each experiment. It was difficult to relate the gel properties to the concentrations of the gelling agents since only one-half to two-thirds of the fuel compartment could be gelled. In general, concentrations of gelling agents were greater than 4 percent.

Initial experiments with the compartmented fuel tank were made to establish a procedure for obtaining consistently firm gels in the tank area adjacent to the hole. After this had been accomplished, the spring-loaded plug was activated just prior to injecting the gelling agents. The simulated compartmented fuel tank could not be sealed by injecting gelling agents following withdrawal of the plug.

CONCLUSIONS

Fuel gelation, especially where it pertains to gels containing low concentrations of solids, does not appear to be a promising method for sealing fuel tanks. Reliable sealing was not obtained with gelling agents in either the multiwalled fuel tank or the compartmented fuel tank. The principal difficulties were as follows:

1. The timing involved in creating a seal with gelling agents is very critical. Once a stream of fuel has broken through at the point of projectile penetration, sealing becomes unlikely.

2. Because fuel gelation is a chemical reaction, the capability for sealing is temperature dependent. Fuel gelling agents act more rapidly at high temperatures than at low temperatures.

3. Rate of reaction is not the only factor affecting the suitability of rapid fuel gelation as a means ot sealing fuel tanks. Although

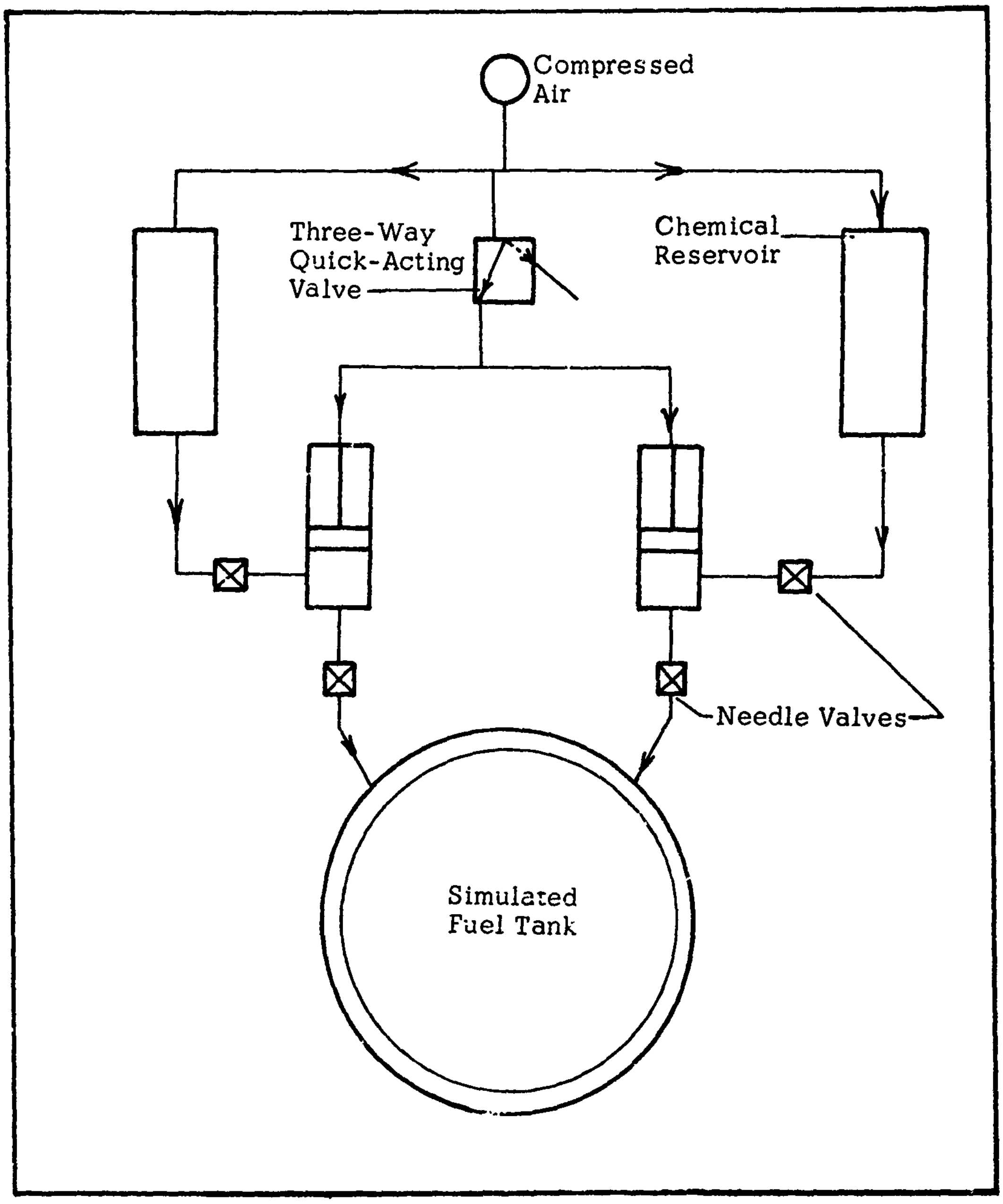


Figure 3. (U) Schematic of Apparatus for Injecting Gelling Agent Into the Simulated Compartmented Fuel Tank.

the chemical reactions involved in fuel gelation can be rapid, fuel does not solidify immediately. Under the turbulent conditions immediately following projectile penetration, the gels behave as fluids (shear thinning). The gels do not develop strength until after they have had an opportunity to set. By the time setting has occurred, the tank fluid may have created a channel and the sealing has been lost.

4. The blending of the gelling agents with each other and with the fuel is dependent upon the size and energy of the projectile and upon the type of penetration. Because these factors vary extensively, gel concentrations and seal quality are determined haphazardly.

5. Gels, especially those containing low concentrations of solids, do not develop high strengths even after setting. It is unlikely that these materials would consistently be able to bridge the holes caused by projectiles 9 mm and larger.

Because of these difficulties experienced with fuel gelation as a means of sealing fuel tanks, this technique was not evaluated in the large-scale ballistic testing phase of this program.

(U) PREFORMED GELS AS FUEL TANK SEALANTS

Gels containing high concentrations of solids (greater than 20 percent) possess properties which suit them better for utilization as fuel tank sealing materials. The principal advantage gained with greater solids is strength. With greater solids concentrations, the gels possess to a lesser degree the tendency to flow under conditions of turbulence. Some gels containing high solids concentrations are shear thickening.

Additional advantages are gained by the use of preformed gels as fuel tank sealants. Two of these advantages are:

1. Simplicity - the sealant is a single material contained in a double-walled tank. Its action is independent of blending or temperature.

2. Quality of seal - the properties of the gel can be established under more carefully controlled conditions than can be accomplished when the gelation is the result of projectile penetration.

Two types of preformed gels were investigated as fuel tank sealing materials. The experimental procedure, experimental results and conclusions are discussed in general terms in the following section. A tabulation of experimental data and a more detailed presentation of experimental results are given in Appendix II.

CRYSTALLINE GELS AS FUEL TANK SEALANTS

Certain fatty acids, when dissolved in liquid hydrocarbons and reacted with sodium or potassium hydroxide, form strong fibrous gels. The strength of these gels is due to the degree of orientation existing between the soap micelles in the gel. When used as a sealing material, the crystalline gel possesses the capability of realigning itself along the path created by a projectile passing through it, thus producing new gel fibers. The newly formed gel fibers slip into the projectile hole, creating a seal.

The capability of the crystalline gel as a fuel tank sealant was tested in double-walled fuel containers with 9 mm projectiles. The target apparatus was designed so that the following factors could be varied:

1. The distance between the walls could be 1/4 inch or larger.

2. The head of fuel above the seal could be varied between 1 and 3 feet.

The target apparatus is schematically represented in Figure 2.

The crystalline gel used in the first experiments consisted of 20 percent solids. A slight improvement in sealing performance was experienced by increasing the solids content to 30 percent.

The experimental results establish the following capabilities for the crystalline gel:

1. The crystalline gel is capable of reliably sealing the entrance holes created by 9 mm projectiles when these holes have been reduced in size by a partial sealing material such as soft rubbe . This sealing can be performed against heads of fuel ranging up to 3 feet.

2. Whenever the partial sealing material has not been used to reduce the size of the 9 mm projectile hole, sealing has been inconsistent.

3. Exit holes produced by 9 mm projectiles cannot be sealed with the crystalline gel.

Sealing the holes created by 9 mm projectiles is very near the maximum capability for the crystalline gel. This material was not selected for testing with larger caliber projectiles.

DILATANT GELS AS FUEL TANK SEALANTS

Some gels containing high concentrations of solids are dilatant. When affected by forces of slight magnitude, these gels behave as viscous liquids. However, under conditions of rapidly changing stress, such as that immediately following projectile impact, the gel behaves as an elastic rubber. The tank sealing capability of the dilatant gels depends upon their ability to absorb part of the energy of the projectile impact and then to react like rubber to close the hole. The dilatant gels then flow together to complete the seal.

Three different dilatant formulations were developed:

No. 1	Xylene	25 wt. %
	JP-4	25 wt. %
	Polystyrene	49 wt. %
	Nylon fiber	1 wt. %
No. 2	Xylene	25 wt. %
	Dimethyl sulfoxide	25 wt. %
	Polystyrene	49 wt. %
	Nylon fiber	1 wt. %

No. 3	Carbon tetrachloride	59 wt. %
	Polystyrene	40 wt. %
	Nylon fiber	1 wt. %

All three are successful sealants.

The effect of contact between hydrocarbon fuels such as JP-4 and these dilatant gels is to coagulate the polystyrene and create a film at the interface between the gel and the fuel. Dilatant gels of the types described above make strong seals which grow stronger with time.

Small-scale ballistics testing was performed on dilatant gel sealants; the procedure and apparatus discussed on pages 9 and 10 were used.

The experimental results establish the following capabilities for the dilatant gel:

1. The dilatant gel is capable of instantly and completely sealing the holes created by 9 mm projectiles. No partial sealing materials are required.

2. The dilatant gels were not capable of sealing exit holes created by 9 mm projectiles.

The performance of the dilatant gels suggests that they can be used for sealing holes created by projectiles larger than 9 mm. The dilatant gels were selected for 20 mm testing.

(U) FOAMS AS FUEL TANK SEALANTS

Because they increase in volume, polymeric foaming reactions are capable of replacing sealant material that has been diluted with fuel or lost from the projectiles impact area. For this reason, and because polymeric foams make strong, permanent seals, foams have been investigated as fuel tank sealing materials.

The development of foaming formulations is discussed in general terms in the following section. A detailed tabulation of experimental results is included in Appendix III.

The criteria for selecting foaming materials to be tested as fuel tank sealants are as follows:

1. The foaming and polymerization reactions must be simultaneous and very rapid (complete in 1 to 2 seconds).

2. The increase in volume in going from monomer to foam must be considerable (8 - 15 times).

3. The cured foam must be closed pore and able to prevent passage of fuel; it must be insoluble and chemically resistant to fuel.

Three types of foaming materials have been investigated as potential fuel tank sealants:

1. Silicone foams.

2. Polyurea foams.

3. Polyurethane foams.

Table I presents a comparison of some of the properties of the most attractive representatives of each type of foaming material.

The polyurethane foaming formulation, Pluracol EDP-500✦ and toluene diisocyanate,✦✦ was selected for small-scale ballistic testing because it rapidly developed large quantities of strong, rigid foam. Although the rate of foam formation is somewhat slower than with the polyurea foam, the strength and quantity of the foam produced were considerably greater.

Efforts were directed toward increasing the rate of reaction of the Pluracol EDP-500 with toluene diisocyanate, and especially toward overcoming the requirement for manual stirring. It was found that an addition of about 20 weight percent dimethyl sulfoxide and a trace amount of water

✦ Product of Wyandotte Chemical Corporation
✦✦ Hylene TM-65, Product of E. I. Dupont De Nemours, Inc.

TABLE I
COMPARISON OF FOAMING MATERIALS

Type of Material	Reaction* Start (seconds)	Reaction Complete (seconds)	Product
Silicone	20	90	Tough, flexible foam
Polyurea	6	10	Brittle foam easily crumbled
Polyurethane	12	30	Tough, rigid foam

* Reactants are thoroughly blended before timing is begun.

could cause the reaction to be completed in less than 2 seconds at ambient temperatures above 50^0F. The following two-component formulation was used at temperatures of 50^0F and above:

Component No. 1	37.4% by weight	Hylene TM-65
Component No. 2	42.9% by weight	Pluracol EDP-500
	16.1% by weight	Dimethyl sulfoxide
	0.8% by weight	Water
	2.8% by weight	Stannous octoate

At low temperatures, polyurethane foams become ineffective as fuel tank sealants primarily because their sealing capability depends upon a chemical reaction. The effect of cold is to reduce the rate of both the polymerization and the foaming reactions and to reduce the volume of foam produced. These effects are illustrated in Figures 4 and 5. In order to extend the effectiveness of the polyurethane foam to lower temperatures, a second formulation was developed which increased the reaction rates and the quantity of foam produced at temperatures between 32^0 and 45^0F. Complete cures could be obtained at the low temperatures in less than ten seconds with the following formulation:

Component No. 1	35.4% by weight	Hylene TM-65
Component No. 2	40.5% by weight	Pluracol EDP-500
	16.6% by weight	Dimethyl sulfoxide
	3.5% by weight	Water
	2.5% by weight	Aniline
	1.5% by weight	Stannous octoate

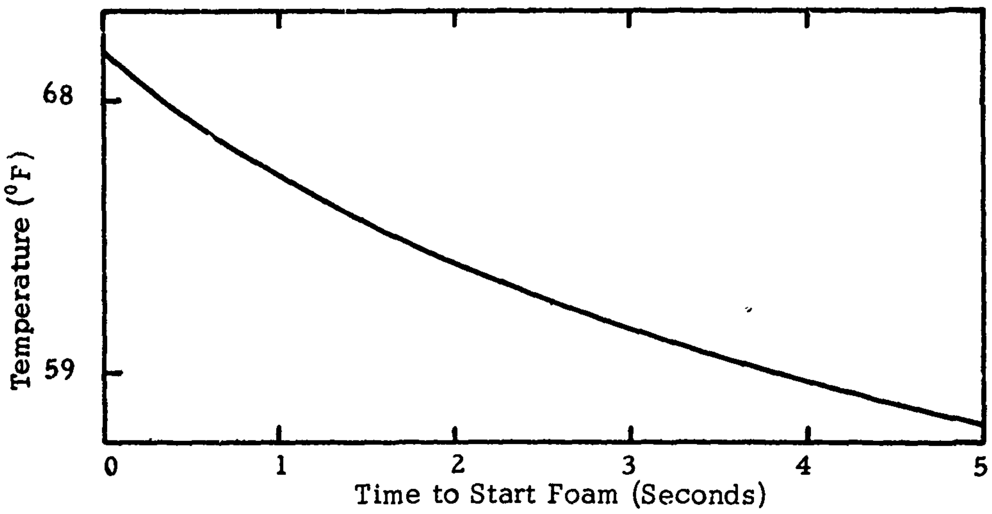


Figure 4. (U) Time to Start of Polyurethane Foam Production vs Temperature.

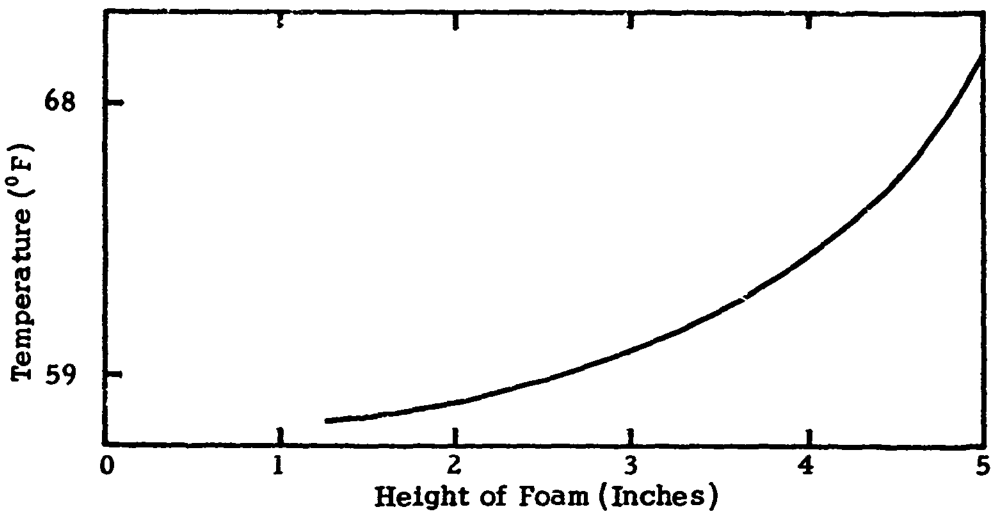


Figure 5. (U) Quantity of Polyurethane Foam Produced vs Reagent Temperature.

The fuel tank sealing capability of the polyurethane foam was tested with 9 mm projectiles. The experimental procedure and apparatus were similar to those described on pages 10 and 12.

The polyurethane foam was utilized in two ways:

1. Component No. 2 was suspended in bags or plastic containers in Component No. 1.

2. Components No. 1 and 2 were contained separately between the walls of a three-wall fuel container. More effective results were obtained, especially at low temperatures, when the two components were separated by a frangible wall, such as glass or Lucite. Projectile penetration shatters the partition, thus causing increased blending of components.

The results of small-scale ballistic testing established the following capabilities for the polyurethane foam sealing material:

1. Polyurethane foams, formulated as described above, are capable of sealing the entrance holes created by 9 mm projectiles. Complete sealing occurs in less than 1 second, with very little loss of fuel. Seals may be obtained against the pressure created by a 3-foot head of fuel.

2. The sealing function of polyurethane foams is most effective when the sealant components are separated by a frangible partition that shatters as a result of projectile penetration.

3. Sealing can be obtained against 9 mm ammunition down to 40^0F using the cold weather formulation and the frangible partition. At lower temperatures, one of the components must be preheated.

4. Effective sealing of 9 mm projectile holes has been obtained only when the projectile passes from Component No. 1 containing Pluracol EDP-500 to Component No. 2 containing Hylene TM-65.

5. Sealing of 9 mm exit holes was not accomplished with the polyurethane foam.

Because the polyurethane foam possesses the apparent capability for effectively sealing holes caused by projectiles larger than 9 mm, it was selected for large-scale ballistics testing with 50-caliber and 20 mm ammunition.

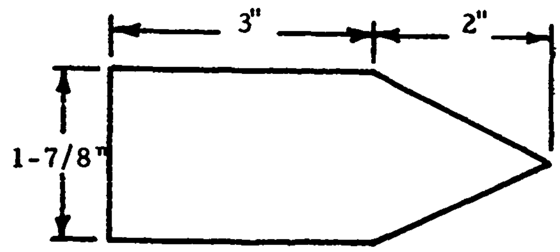
(C) LARGE-SCALE BALLISTICS TESTING (U)

(U) Two different self-sealing materials were selected on the basis of their performance during small-scale testing for evaluation with 50-caliber, 20 mm and larger projectiles. The materials selected were the dilatant gel and the polyurethane foam discussed previously.

(U) EQUIPMENT AND PROCEDURE

Two projectile firing devices, one 50-caliber and the other 20 mm, were assembled and mounted for large-scale field testing. The two devices are illustrated in Figures 6 and 7. Larger than 20 mm projectiles were fired from a Western Company air gun. All three of these devices were remotely fired electrically.

Projectiles used during field testing have been 50-caliber armor-piercing, M-2, 20 mm target-practice, M-55A-2; and 20 mm armor-piercing incendiary, M-53. The larger than 20 mm projectile was made from 1/4-inch steel plate and weighed 7 ounces. Its dimensions are diagrammed below.



The target fuel tank used in the large-scale field tests is illustrated in Figure 8. Test panels containing sealant were bolted over the windows, and the tank was filled to a predetermined level with fuel or water. In most of the large-scale tests, water has been used instead of fuel. Provisions have been made for a third panel to be fastened to the baffle inside the tank and thus to create a compartmented tank. The tank was mounted on a 3/4-inch-thick piece of aluminum to prevent the tank's tipping over.

The self-sealing panels were of two types, as illustrated in Figures 9 and 10. The single compartmented panel was used with the dilatant gel, and the double compartmented panel was used with the polyurethane foam. Panel thickness was varied, and the panel covers were from any one of several materials.

Several panel covering materials have been used in this phase of the program which possess high strength. The properties of these materials are summarized in Table II. The ARM-021 and the nylon felt are porous and

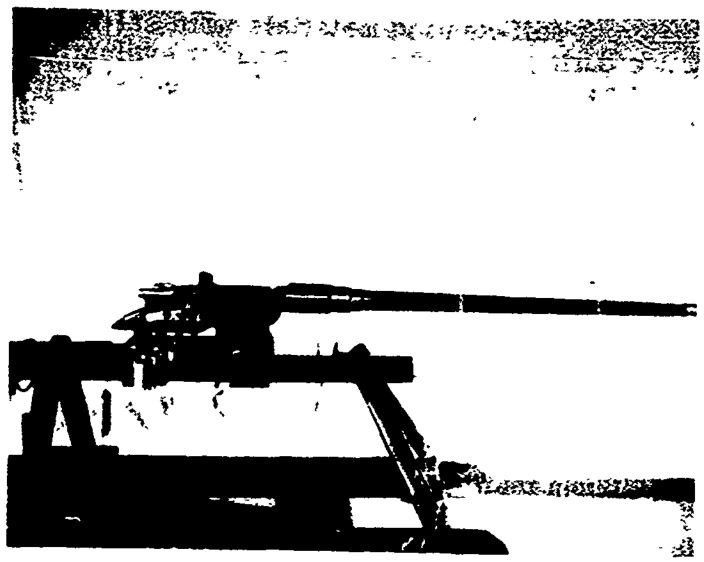


Figure 6. (U) 50-Caliber Gun.

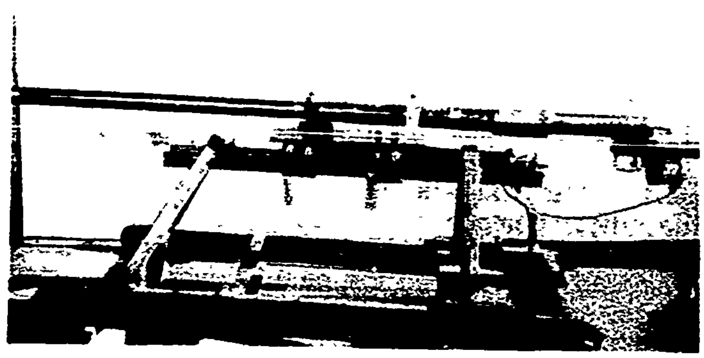


Figure 7. (U) 20 mm Gun.

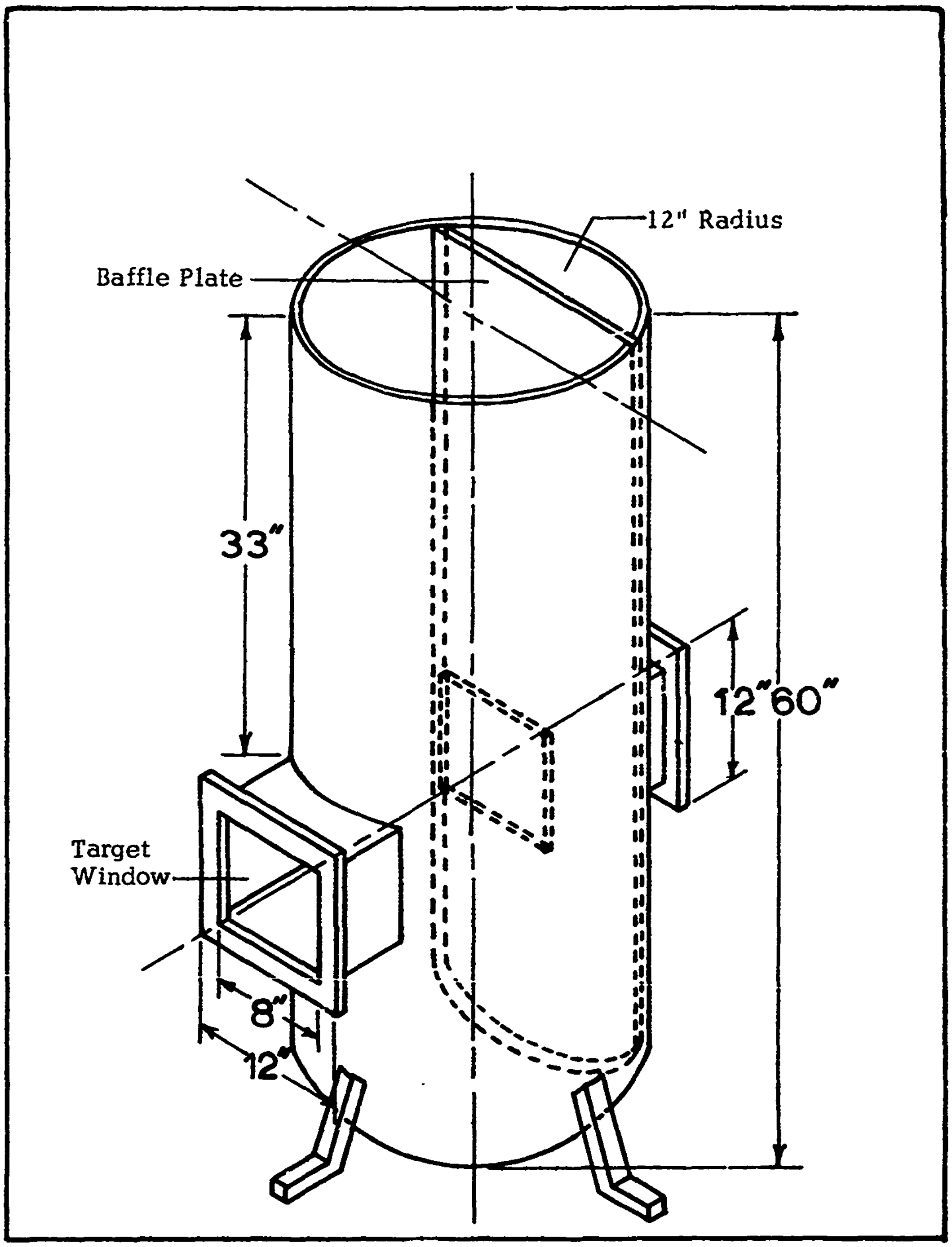


Figure 8. (U) Target Tank Apparatus.

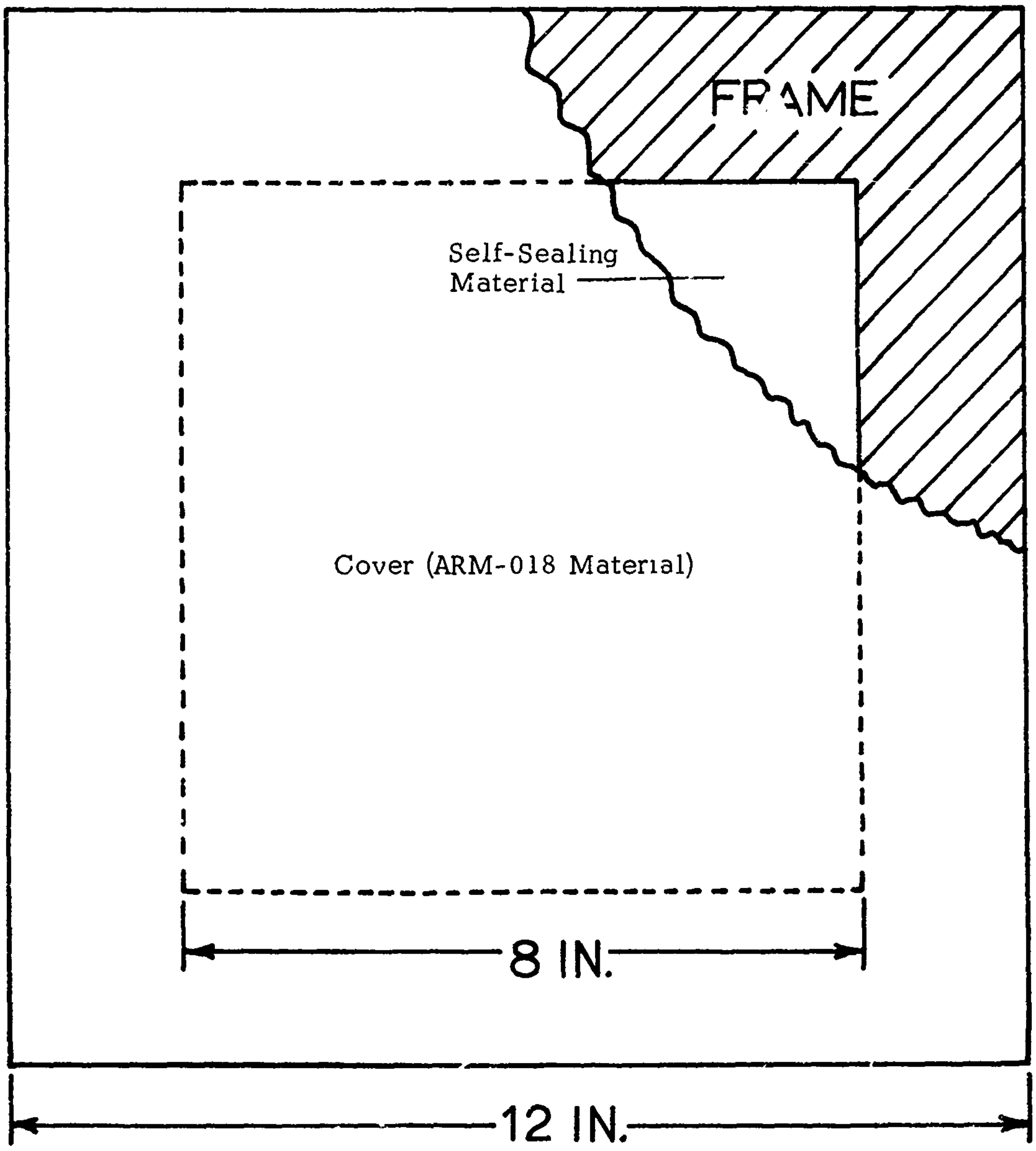


Figure 9. (U) Test Panel.

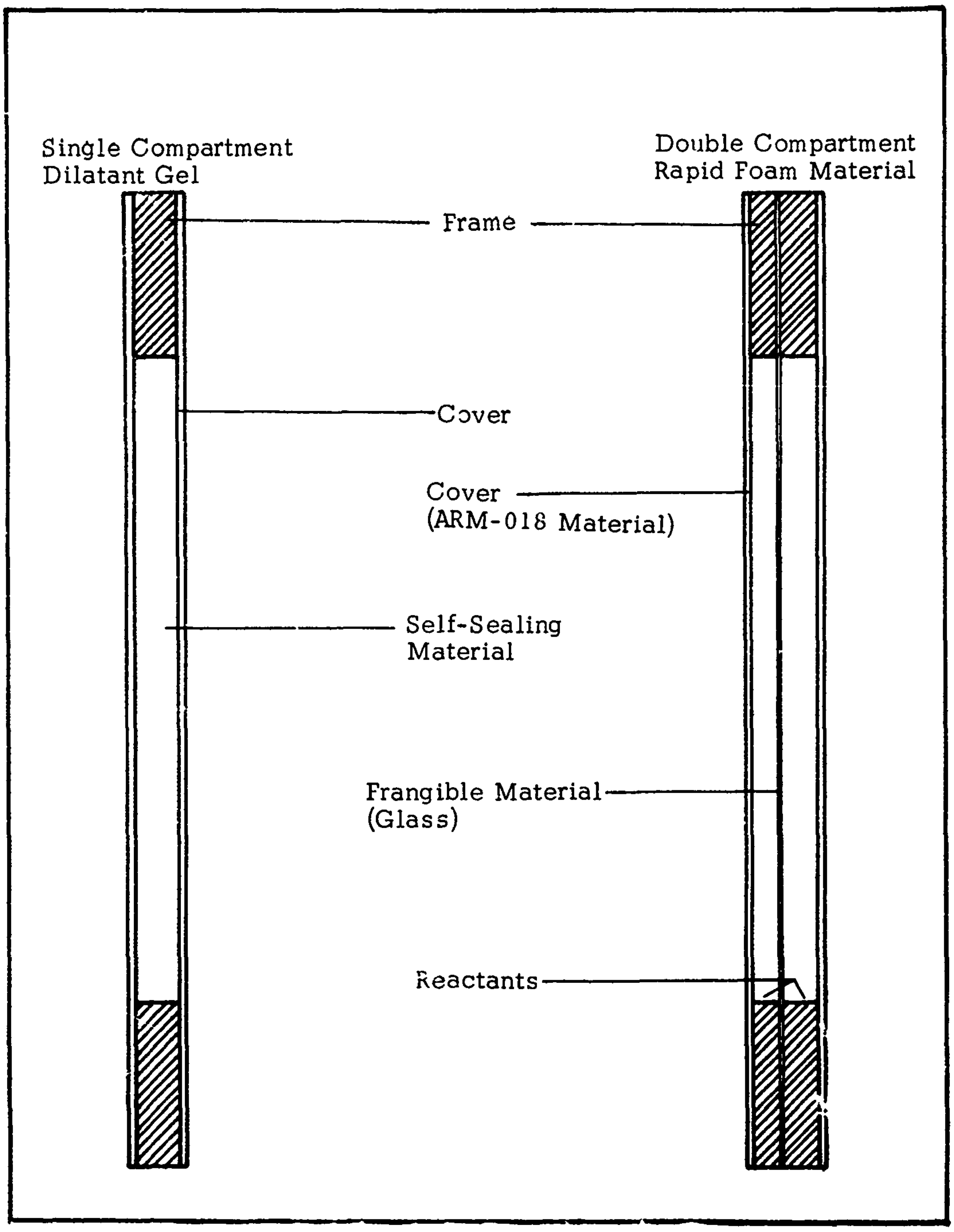


Figure 10. (U) Test Panel Cross Section.

TABLE II
(U) PROPERTIES OF PANEL COVERING MATERIALS

Manfacturer's Designation	Composition	Wt. /Ft.^{2} (pounds)	Thickness (inches)
ARM-018*	resin impregnated 3-ply nylon, 90^0 weave orientation	0.35	0.07 - 0.1
ARM-021*	7-ply nylon, 90^0 weave orientation	0.62	0.07
Ballistic Nylon Felt**	nylon felt	0.37	0.37

* Product of Goodyear Aerospace, Inc.
** Product of the Felters Corporation

require a backing material. All three materials are flexible, elastic, and highly tear resistant.

The arrangement of the equipment during field testing is diagrammed in Figure 11.

(C) RESULTS (U)

(C) The experiments performed with 50-caliber and 20 mm projectiles on the polyurethane foam and dilatant gel sealing agents are outlined in Table III. The first tests were performed with 50-caliber projectiles since 20 mm ammunition had not yet been obtained. One-fourth-inch-thick panels covered with ARM-018 material were able to seal 50-caliber entrance holes reproducibly. The exit holes could not be sealed. In Experiment 5, the 1/4-inch dilatant gel panel was not able to withstand the impact of a 20 mm projectile, and neither entrance nor exit was sealed. One-half-inch panels were used with 20 mm testing for the rest of the large-scale testing. Successful entrance hole seals with dilatant gel and polyurethane foam self-sealing panels are shown in Figures 12 and 13.

(C) Although reliable entrance seals have generally been achieved, the exit panels in every case have been split open or torn, reducing any chance of sealing. Figure 14 shows the damage caused to an ARM-018 panel by an exiting 50-caliber projectile. The damage caused by a 20 mm exit on a similar panel is shown in Figure 15. High-speed motion pictures taken at 1000 frames per second establish the following sequence of events for projectile exit:

1. The projectile strikes the panel and simultaneously causes the walls of the panel to stretch taut.

2. One millisecond later, before the panel can relax, a fluid pressure pulse hits the panel, causing the panel to tear. The tear starts at the hole created by the projectile and proceeds in four directions along the weave of the panel covering material. The sealant material is thrown out of the panel at this time.

3. About 100 milliseconds later, fluid begins to flow from the tank through the torn panel.

(U) The principal cause of the damage to the exit panels is the hydrostatic ram pulse that accompanies the projectile through the fluid in the tanks. This pressure pulse strikes the exit panel immediately after the projectile exits the tank. It has been established that fuel tank bladder materials that have the ability to deform to extreme contours are the most likely not to rupture during crashes. The effect of the hydrostatic ram pulse against the small rigid exit test panel is extremely severe. The tensile stress induced in the panel by this force is distributed only over the 64-inch square of the panel surface; and, with no additional support, the panel bursts.

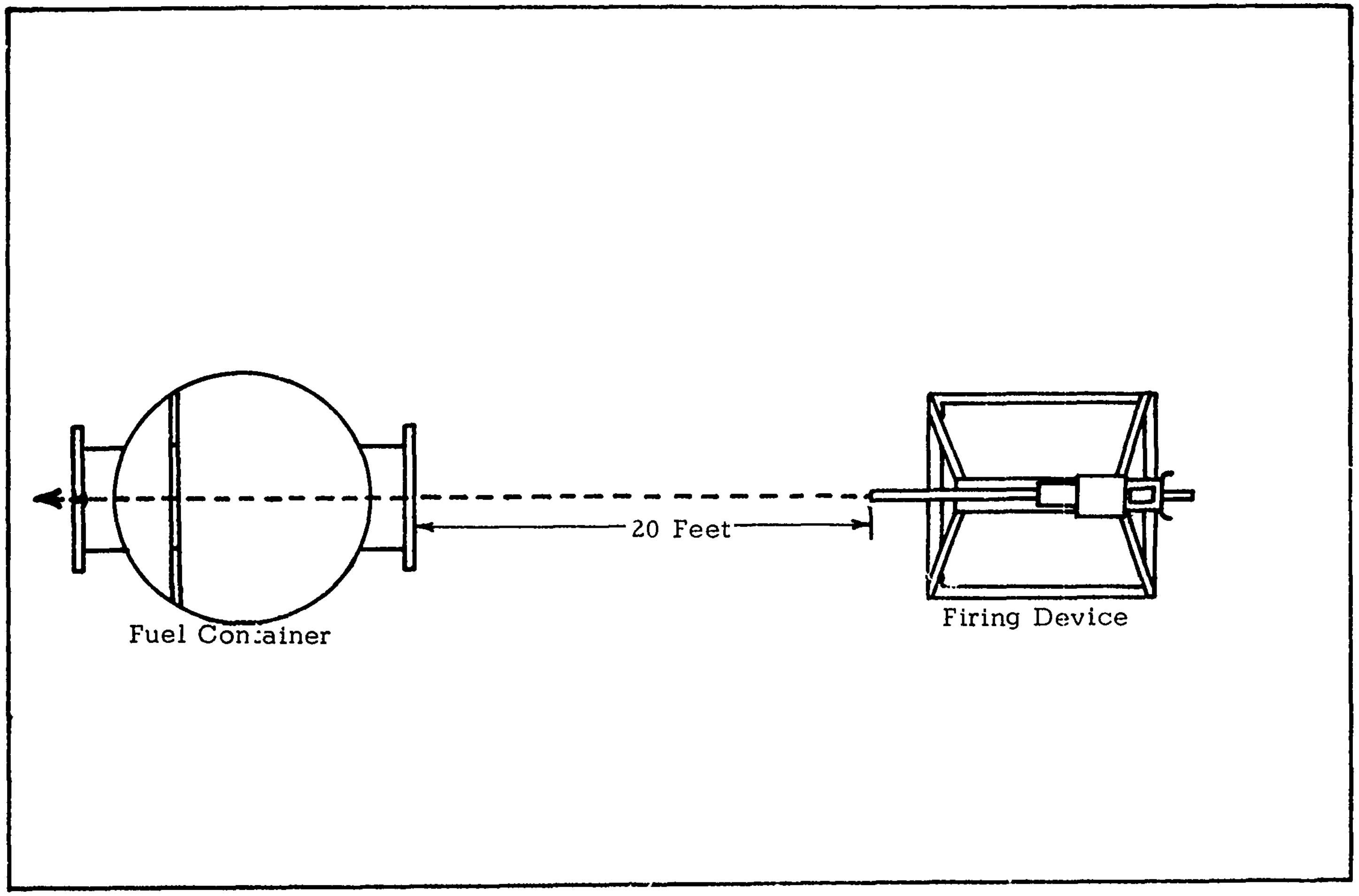


Figure 11. (U) Arrangement of Large Scale Test Equipment.

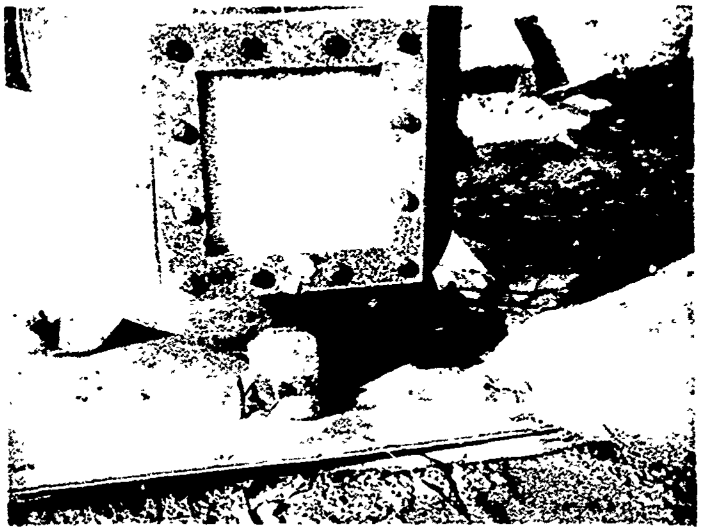


Figure 12. (U) Entrance Seal - Dilatant Gel Panel.

Figure 13. (U) Entrance Seal - Polyurethane Foam.

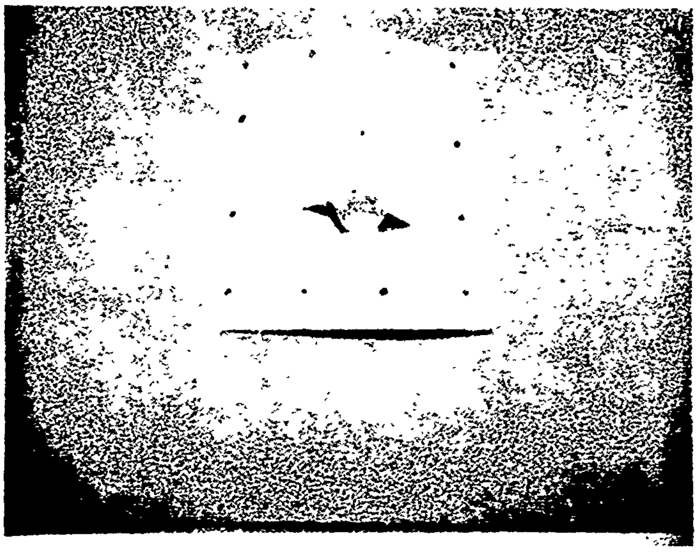


Figure 14. (U) Damage to Exit Panel Caused by 50-Caliber Projectile.

Figure 15. (U) Damage to Exit Panel Caused by 20 mm Projectile.

Rigid materials are not capable of furnishing sufficient support. For example, it was shown in Experiment 7 in Table III that 1/32-inch steel sheet reinforcement could not contain the pressure pulse, and the panel was split open as badly as before.

(C) Experiments 6 through 13 represent efforts at reducing the damage caused by 20 mm projectiles at the entrance panel. In Experiments 6 and 7, the aluminum and steel reinforcement was added to the entrance and exit panels. Figure 16 shows the aluminum reinforced entrance panel after projectile impact. In Experiments 8 and 9, the ARM-018 material was replaced with a very flexible material, latex rubber, and a tear resistant material, Mylar. In Experiments 10 and 11, air spaces were provided between the fluid in the tank and the self-sealing panels in order to prevent the damaging fluid pressure pulse from reaching the panel. In Experiment 12, a baffle was placed in the tank for the purpose of dampening the pressure pulse. In Experiment 13, the tank was filled with open pore industrial foam[1] for the purpose of dampening the pressure pulse. None of these experiments proved to be successful in reducing the damage to the exit panel caused by the passage of a 20 mm projectile.

(U) Two new fuel tank construction materials have been developed which possess tremendous resistance to tear. These materials, the ARM-021 and the ballistic nylon felt, have been used in the remaining experiments to reduce damage to test panels caused by projectile exit.

(C) The ARM-021 material is effective in preventing exit panels from tearing open. Nevertheless, the exit holes are still large, and exit seals have not been obtained. The ARM-021 material has been used by itself in Experiments 14, 19, and 24. In Experiment 18, the ARM-021 was backed up with the nylon felt material.

(C) Because ballistic nylon felt is porous, it has been used only as a backup material for the ARM-018 and ARM-021 materials. The felt does not tear. However, since it is elastic, it stretches away from the panel during projectile impact. This removes the support from the panel which is damaged as before by the hydrostatic pulse. Ballistic nylon felt is used in Experiments 15, 16, 17, and 18. No exit seals have been obtained with this material.

(C) The polyurethane self-sealing material was tested in Experiments 21 through 24. Entrance seals were obtained with the polyurethane sealant in Experiments 21 and 22. However, very little foam was formed at the point of projectile exit, and no exit seals were achieved.

[1] 10 pores per inch foam - product of the Scott Corporation

Figure 16. (U) Entrance Seal - Dilatant Gel Panel of Aluminum Reinforcement.

(C) Rigid supporting materials have not been successful in preventing damage to exit panels. However, in compartmented fuel tanks in which the exit self-sealing panel is backed by additional fuel, complete, instantaneous seals have been achieved. Although the interior panel seals, the tank exit panel is badly damaged. These results were obtained in Experiments 20, 23, and 24, with both the polyurethane foam and the dilatant gel sealants. For these experiments, the fuel tank was modified into a compartmented tank in which the compartment partition could be fitted with a self-sealing panel. In compartmented fuel tanks in which the self-sealing panels were backed by fuel, part of the fuel was lost. However, the bulk of the tank's fuel capacity was retained.

(C) The capability of the dilatant gel to seal holes created by larger than 20 mm projectiles was tested in Experiment 19. A pointed projectile measuring 1-7/8 inches by 5 inches by 1/4 inch was fired at close range from an air gun at the experimental fuel tank, protected by dilatant gel self-sealing panels. The projectile passes through the entrance and exit panels, but no seals were obtained. The passage of this projectile created slits in the test panels approximately 2 inches long. Apparently, the projectile sliced through the panels, not imparting enough energy to the sealant to cause it to reflex over the hole.

(U) In Experiment 24, an armor-piercing incendiary projectile was fired at the experimental fuel tank. The tank was compartmented, and the interior panel was backed by the tank fluid, which was water. The tank was protected by polyurethane self-sealing panels.

(C) Experiment 24 was designed to measure the ability of the polyurethane sealing system to seal the holes created by an activated 20 mm A. P. I. round. At initial impact, this projectile is split into several pieces. The jacket disintegrates; as a result, incendiary materials and the armor-piercing portion of the projectile are exposed. There was no evidence that the sealing requirements for an A. P. I. round are more severe than for the TP rounds used previously. No attempt has been made in Experiment 24 to test the fire-preventing abilities of the sealing system being discussed. With the compartmented tank, there is always some fuel spillage which is very likely to be ignited as the incendiary round impacts the ground. Once ignited, the fire will flash back and ignite the tank in spite of any self-sealing and fire-extinguishing contributions at the tank. For this reason, incendiary projectiles were not fired through flammable fuels.

(C) In general, it has not been possible to grade sealing capability as a function of the amount of tank fluid lost prior to sealing or the amount of leakage after sealing has occurred. Entrance seals have usually been instantaneous and complete, and the damage occurring at the exit panel has made measurement of the rate of leakage impractical. Evaluation of the entrance panel is accomplished by reviewing motion pictures of the experiment and, in some cases, by refilling the tank after the exit panel has been repaired. The evaluation of the sealing in compartmented tanks is accomplished by reviewing films and by measuring the quantity of fluid remaining in the sealed compartment before and after the experiment.

TABLE III (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

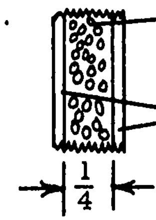
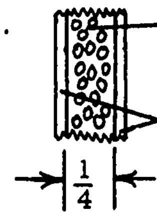
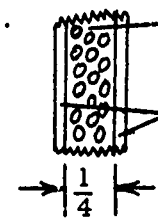
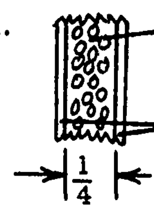
Experiment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
1	Dilatant Gel	0.50 cal. A.P.	 Dilatant Gel; Goodyear ARM-018; $\frac{1}{4}$	Same as Entrance	None	Entrance Only	Entrance seal instantaneous and complete. Exit Panel split open and sealant thrown out.
2	Dilatant Gel	0.50 cal. A.P.	 Dilatant Gel; Goodyear ARM-018; $\frac{1}{4}$	Same as Entrance	None	Entrance Only	Same as Experiment 1.
3	Dilatant Gel	0.50 cal. A.P.	 Dilatant Gel; Rigid Fiberglass; $\frac{1}{4}$	Same as Entrance	None	None	Both entrance and exit panel's demolished.
4	Dilatant Gel	0.50 cal. A.P.	 Dilatant Gel; Goodyear ARM-018; $\frac{1}{4}$	Same as Entrance but w/ Rigid Fiberglass Backing	None	Entrance Only	Entrance seal instantaneous and complete. Exit panel demolished.

TABLE III (Cont.) (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

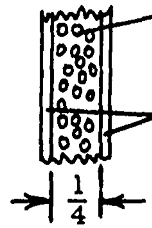
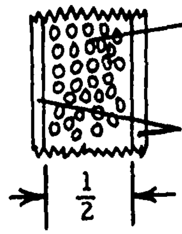
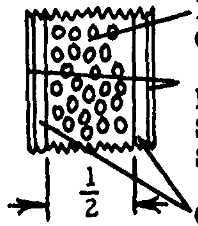
Experiment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
5	Dilatant Gel	20 mm T.P.	 Dilatant Gel; Goodyear ARM-018; 1/4	Same as Entrance	None	None	Both entrance and exit panels split open.
6	Dilatant Gel	20 mm T.P.	 Dilatant Gel; 0.025" Hard Aluminum; 1/2	Same as Entrance	None	Entrance Only	0.025" hard aluminum sheet was used to reinforce both panels. Aluminum was split open at entrance panel and sheared away at exit panel. Entrance seal had slight leak.
7	Dilatant Gel	20 mm T.P.	 Dilatant Gel, Perforated Steel Sheet; Goodyear ARM-018; 1/2	Same as Entrance	None	Entrance Only	Entrance and exit panels reinforced with 1/32" perforated steel sheet with 1/16" holes spaced on 1/8" centers. Entrance seal instantaneous and complete. Exit panel split open. Steel sheet sheared from panel.

TABLE III (Cont.) (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

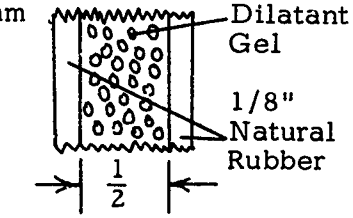
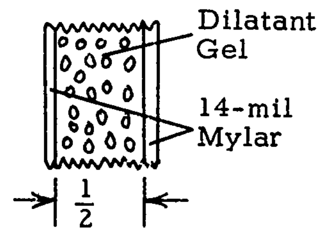
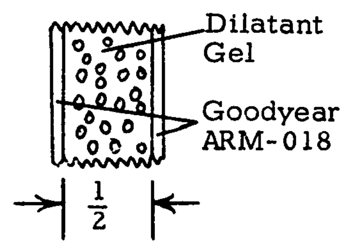
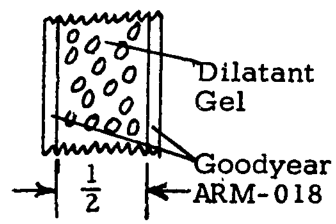
Exper-iment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
8	Dilatant Gel	20 mm T.P.		Same as Entrance	None	None	Panels covered with natural rubber. Both panels split open.
9	Dilatant Gel	20 mm T.P.		Same as Entrance	None	None	Panels covered with Mylar. Both panels split open.
10	Dilatant Gel	20 mm T.P.		Same as Entrance	None	Entrance Only	Fuel was contained in polyethylene tank, leaving 2" air space between fuel and panels. Entrance seal instantaneous and complete. Exit panel split open.
11	Dilatant Gel	20 mm T.P.		Same as Entrance	None	Entrance Only	An 18" air space was provided in front of exit panel. Entrance seal instantaneous and

TABLE III (Cont.) (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

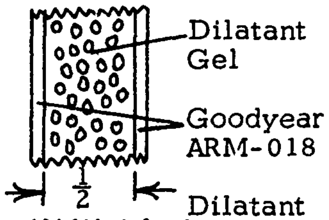
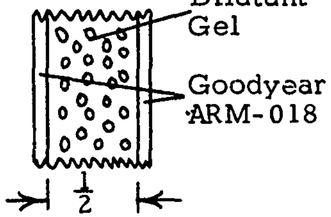
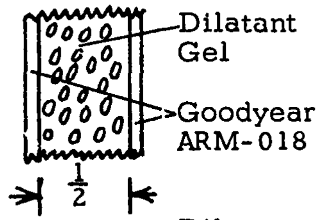
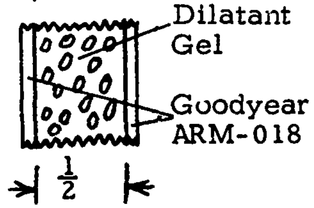
Experiment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
							complete. Exit panel split open.
12	Dilatant Gel	20 mm T.P.		Same as Entrance	None	Entrance Only	Tank was provided with baffle. Entrance seal instantaneous. Exit panel split open.
13	Dilatant Gel	20 mm T.P.		Same as Entrance	None	Entrance Only	Tank completely filled with open pore industrial foam (97% void). Entrance seal instantaneous and complete. Exit panel split open.
14	Dilatant Gel	20 mm T.P.		Same as Entrance Except Back Panel Cover Is ARM-021	None	Entrance Only	Entrance seal instantaneous and complete. Damage to exit panel not as complete as with ARM-018.
15	Dilatant Gel	20 mm T.P.		Same as Entrance, Except a 3/8" Thick Nylon Felt Backing Was Put	None	Entrance Only	Entrance seal instantaneous and complete. At exit panel ARM-018 split open. Nylon felt stretched but intact.

TABLE III (Cont.) (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

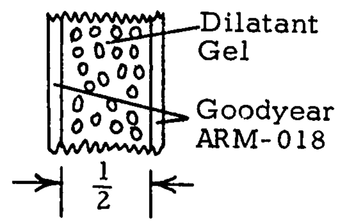
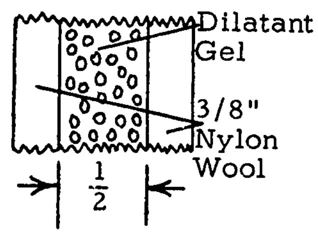
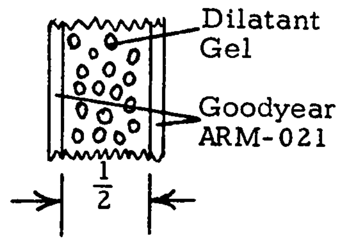
Experiment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
				On Outside			
16	Dilatant Gel	20 mm T.P.		Same as Entrance, Except a 3/8" Thick Nylon Felt Backing Was Put On Outside	None	Entry, Partial Exit, Partial	One-sixth gallon per minute lost from entrance panel. Two gallons per minute lost from exit hole.
17	Dilatant Gel	20 mm T.P.		Same as Entrance	None	None	Panel covers badly stretched though not torn. Sealant without support of covering material does not seal.
18	Dilatant Gel	20 mm T.P.		Same as Entrance, Except a 3/8" Nylon Wool Was Used on the Backside	None	Entrance Only Exit, Partial	Entrance seal instantaneous and complete. Projectile exit hole was sealed. However, panel cover was sheared where it was attached to tank. This was source of fuel loss.

TABLE III (Cont.) (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

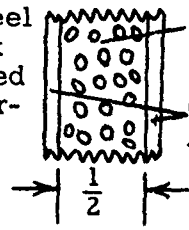
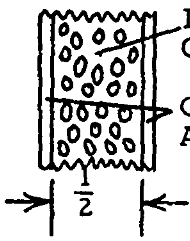
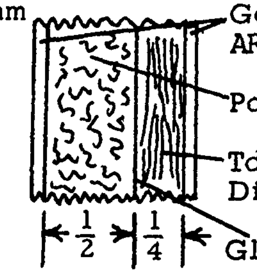
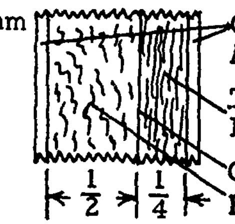
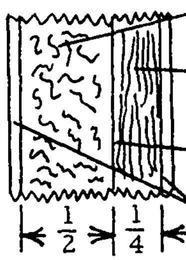
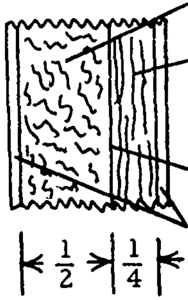
Experiment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
19	Dilatant Gel	Flat Steel 1-7/8" x 1/4" Fired From Air-gun		Same as Entrance, Except ARM-018 Was Used Instead of ARM-021	None	None	2" slits torn in panel at projectile entrance and exit.
20	Dilatant Gel	20 mm T.P.		Same as Entrance	Same as Entrance	Entrance and Middle Only	Middle panel surrounded by fuel. Seals at exit and middle panels instantaneous and complete. Exit panel split open.
21	Polyurethane Foam	20 mm T.P.		Same as Entrance	None	Entrance Only	Entrance seal within one second. Very slight loss of fuel. Very little foam produced near point of projectile exit.
22	Polyurethane Foam	20 mm T.P.		Same as Entrance	None	Entrance Only	Same as Experiment 21.

TABLE III (Cont.) (C)
LARGE-SCALE LIVE AMMUNITION TESTING (U)

Experiment	Sealant	Projectile	Entrance Panel	Exit Panel	Middle Panel	Seal	Comments
23	Polyurethane Foam	20 mm T.P.		Same as Entrance	Same as Entrance	Entrance and Middle Only	Middle panel surrounded by fuel. Seals at exit and middle panels instantaneous and complete. Exit panel split open.
24	Polyurethane	20 mm A.P.I.		Same as Entrance Except ARM-018 Was Used.	Same as Entrance	Entrance and Middle Only	Same as Experiment 23. No apparent extra damage caused by functioning incendiary sound.

(U) OPERATIONAL CONSIDERATION FOR THE DEVELOPMENT OF SELF-SEALING FUEL TANKS

In order to develop the polyurethane foam and the dilatant gel into operational self-sealing materials, that is, to make the transition from the feasible to the practical, a number of factors must be considered. These factors are discussed generally in MIL-T-5578C, "Tank, Fuel, Aircraft, Self-Sealing". The following is a discussion of the dilatant gel and polyurethane self-sealing materials in the light of these operational requirements.

1. Any chemicals slated for use as self-sealing materials, must be capable of maintaining a reasonable storage life. The dilatant gel system has an indefinite storage life, provided the solvents are not permitted to evaporate. The polyurethane foam sealant, however, contains chemicals which react rapidly with one another and will also react with atmospheric oxygen and moisture.

2. The sealing material should not be affected by flexing the tank walls. Flexing should have no effect on the dilatant gel sealant. However, the partition necessary to obtain a rapid reaction with the polyurethane foam may make the tank wall less flexible.

3. The fuel tank must be capable of withstanding temperatures ranging from -65°F to +145°F. In both systems the chemicals are stable throughout this range. The temperature range over which the polyurethane foam can operate is narrow, since sealing with this material is the result of a chemical reaction. The operational temperature range of the dilatant gel is much wider.

4. It is desirable that the tank material be capable of being fabricated in various shapes to conform to individual fuel tank cavity structures. Both fuel tank sealing materials are capable of this.

5. It is also desirable that the tank be capable of being folded to allow installation and removal from a constructed aircraft tank cavity. The folding and unfolding should in no way damage or cause actuation of the self-sealing components of the tank. Tank walls constructed to use the polyurethane foam sealant cannot be folded as well due to the requirement for a frangible partition.

6. Since it is possible that a tank will become damaged during installation or operation, it is essential that chemicals used in the tank construction be relatively harmless to personnel and equipment. A damaged tank must not release any substance which would contaminate the aircraft fuel system. It must also be capable of being replaced without special handling equipment. One of the polyurethane foam reactants is very poisonous and must be handled with care. The dilatant gel, on the other hand, is not dangerous to personnel or usual aircraft materials.

7. The self-sealing material must also be capable of withstanding activation when subjected to the shock and vibration loads expected during normal aircraft operation. Probably both sealant materials can be utilized in such a way as to be free from the danger of inadvertent activation. However, tanks using the polyurethane sealant are more vulnerable to shock because of the rigid construction, greater complexity, and the frangible partition.

8. In order to provide an acceptable system from the standpoint of weight, it may be necessary to consider that 2.5 pounds per foot^2 is a maximum tank weight to provide protection for 20 mm ammunition. The dilatant gel sealant panel weighs about 4.4 pounds per foot^2. This weight can be reduced in three ways.

   a. Reduce the density of the sealing material. The dilatant gel formulation was used with several solvents which resulted in a variation in density. The least dense system would correspond to a 2.9-pound-per-foot^2 panel.

   b. Reduce the quantity of sealing material being used. With larger more flexible self-sealing panels, thinner panels can be used to seal 20 mm projectile holes.

   c. Use the panel covering materials which weigh less.

   The polyurethane panel is exceptionally heavy at 5 pounds per foot^2. Weight reduction possibilities are limited to methods b and c alone.

9. When a compartmented fuel cell is required, it is necessary to consider the need for simplified filling and the reliability of fuel feed and fuel transfer.

(C) CONCLUSIONS (U)

(C) 1. Several of the systems investigated, including the dilatant gels and polyurethane sealing materials, will seal the entrance holes created by 50 caliber and 20 mm ammunition; however, none of the systems investigated would seal the exit holes caused by the projectiles.

(U) 2. Both the dilatant gel and the polyurethane sealing material are very similar in their sealing capability; however, the dilatant gel sealant panel weighs approximately 4.5 pounds per foot^2, and the polyurethane panel weighs approximately 5 pounds per foot^2.

(U) 3. The storage life, operational temperature range, and handling requirements of the dilatant gel are superior to those of the polyurethane system, although both systems have limited applications.

(U) 4. Fuel gelling as a means of decreasing the vulnerability of aircraft fuel systems is feasible; however, due to the inability to seal exit holes and the complexity and weight penalties involved, it appears to be impractical for use with aircraft.

(U) RECOMMENDATIONS

1. The self-sealing test panels used in the subject experimental program were constructed to determine the feasibility of several sealant formulations. No attempts were made to reduce panel weight to the minimum for achieving a given performance. We believe that a sealant panel utilizing the dilatant gel and weighing less than 2.5 pounds per foot^2 can be developed which is effective against 20 mm projectiles. A continuing investigation of the dilatant gel sealant should establish formulations and design panels for an operational system to be used in aircraft.

2. After the weight of the dilatant gel self-sealing material has been minimized, tests should be accomplished in accordance with MIL-T-5578C. The material may be qualified in either the large cubical tank of MIL-T-5578C or in an actual operational tank configuration. The use of large, flexible self-sealing panels will reduce the severity of the exit hole problem experienced during this feasibility study.

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APPENDIX I (U)

EXPERIMENTAL DATA, FUEL TANK SEALING BY FUEL GELATION

SIMULATED MULTIWALL FUEL TANK

The experiments utilizing fuel gelation for sealing in the simulated multiwall fuel tank are presented in Table IV. A detailed discussion of the experiments follows:

1. In Experiments 1 and 2, the sealing agents were not held in vicinity of the hole long enough to react and seal.

2. Starting with Experiment 3, to retain the fatty acid in the area to be sealed long enough for a reaction to take place, the fatty acid was thickened with nylon fiber and an inorganic gelling agent, CAB-O-SIL. To move the thickened fluid over the hole and to bring it in contact with the caustic solution, the walls containing the fatty acid were pressurized. Although a number of mechanical seals were obtained, almost no chemical reaction occurred where the caustic solution and the fatty acid made contact. A mechanical seal refers to the hole being plugged by the thickened fatty acid rather than by the chemical reaction between the caustic solution and the fatty acid.

3. In Experiments 6 and 7, 5 percent (by weight) of fatty acid was dissolved in the fuel to supplement the acid contained in the walls and to increase the quantity of gel formed at the hole. There was no apparent improvement in the quality of seal formed.

4. In Experiment 8, the surface area of the fatty acid was increased by forcing it into the simulated projectile hole through four separate channels. This had no apparent effect on the amount of gel formed in the hole.

9 MM BALLISTICS EXPERIMENTS WITH MULTIWALL FUEL TANKS

To determine whether projectile impact would have an effect on the mixing and ultimately on the reactivity of the gelling agents, small-scale ballistics testing was initiated. These experiments are tabulated in Table V.

In Experiment 11, dimethyl sulfoxide was added to the fatty acid to increase the rate of reaction. Dimethyl sulfoxide is a powerful solvent that will dissolve both the fatty acid and the caustic solution. It often has the ability to increase reaction rates. The dimethyl sulfoxide did not, however, cause the gel to seal the fuel container.

EXPERIMENTS WITH THE SIMULATED COMPARTMENTED FUEL TANK

The experiments with the simulated compartmented fuel tank are outlined in Table VI and are discussed in the following paragraphs:

1. The objective of Experiments 1 through 18 is to establish techniques for reproducibly creating firm gels in the front part of the tank compartment adjacent to the hole. In these experiments, the reagents were injected prior to removing the plug, and the quality and quantity of each gel were determined. In the first seven experiments, the gels formed were fair to poor, slushy in consistency, and not properly placed to create a seal.

2. Inadequate mixing was the cause of the problem. To obtain thorough mixing, 10 percent by weight dimethyl sulfoxide solvent was added to the fatty acid, and the caustic solution was emulsified in JP-4 (20 percent by weight JP-4). These formulations achieved a consistent improvement in gel quality.

3. In Experiments 14 through 18, aiming extensions were attached to the injection nozzles inside the tank compartment. This was to determine whether additional gel improvement could be achieved by redirecting the injections to different parts of the compartment. A decrease in gel sealing capability was experienced when the agents were directed away from the center of the compartment just in back of the hole.

4. In Experiment 19, the procedure that produced the best results (used in Experiments 8 through 14) was duplicated with the exception that the plug was extracted from a tank just prior to injecting the gelling agents. Although a firm gel was ultimately produced, no seal was created. During the turbulent conditions just after injection of the gelling agents, ungelled fuel forced a channel to the hole, and most of the fuel was lost.

TABLE IV
FUEL TANK SEALING EXPERIMENTS
USING GELATION REACTIONS - SIMULATED MULTIWALL FUEL TANK

Experiment	Chemical Compartments				Size of Hole (in.)	Type of Seal		Head of Fuel (ft.)	Comments
	Outside	Inside	Thickness (in.)	Pressurization		Partial	None		
1	50% by wt. aqueous, caustic solution	Fatty acid	1/4	-	1	-	X	1	Gelling agents mixed with fuel spilled out onto the ground. No gelation occurred in the vicinity of the hole.
2	50% by wt. aqueous, caustic solution	Fatty acid	1/4	0.1 atm over acid	1	-	X	1	Gelling agents mixed with fuel spilled out onto the ground. No gelation occurred in the vicinity of the hole.
3	Fatty acid thickened with nylon fibers and CAB-O-SIL	50% by wt. aqueous, caustic solution	1/4	0.2 atm over acid	1	X	-	1.4	Mechanical seal. No appreciable chemical reaction.
4	Fatty acid thickened with nylon fibers and CAB-O-SIL	Nothing	1/4	0.1 atm over acid	1	X	-	1	Mechanical seal.
5	50% by wt. aqueous, caustic solution	Fatty acid thickened with nylon fiber and CAB-O-SIL	1/4	0.1 atm over acid	1	X	-	1	Mechanical seal. No appreciable chemical reaction.

TABLE IV (Cont.)
FUEL TANK SEALING EXPERIMENTS
USING GELATION REACTIONS - SIMULATED MULTIWALL FUEL TANK

Experiment	Chemical Compartments				Size of Hole (in.)	Type of Seal		Head of Fuel (ft.)	Comments
	Outside	Inside	Thickness (in.)	Pressurization		Partial	None		
6	Fatty acid thickened with nylon fibers and CAB-O-SIL	50% by wt. aqueous, caustic solution	1/4	0.15 atm over acid	1	-	X	1	Additional fatty acid dissolved in fuel. No apparent chemical reaction in vicinity of hole.
7	Fatty acid thickened with nylon fibers and CAB-O-SIL	50% by wt. aqueous, caustic solution	1/4	0.15 atm over acid	1	X	-	1	Additional fatty acid dissolved in fuel. Mechanical seal. No apparent chemical reaction in vicinity of hole.
8	50% by wt. aqueous, caustic solution	Fatty acid thickened with nylon fibers and CAB-O-SIL	1/4	0.2 atm over acid	1	-	X		Fatty acid pushed into hole through four 0.23-inch channels to increase reaction at hole. Quantity of reaction increased but not adequate.

TABLE V

FUEL TANK SEALING EXPERIMENTS - FUEL GELATION REACTIONS - MULTIWALL FUEL TANK SYSTEM, 9 MM BALLISTICS TEST

Sealing System	Fuel Head (ft.)	Seal Entrance	Seal None	Comments
Caustic acid 1/2 inch, 1/2 inch caustic outside	1	x	-	-
1/2-inch double interwall, caustic outside	2/3	-	x	-
1/2-inch double interwall, caustic outside	2/3	-	x	DMSO added to increase rate.

TABLE VI
FUEL TANK SEALING EXPERIMENTS USING FUEL GELATION REACTIONS - SIMULATED COMPARTMENTED TANK

Quantity of Caustic Solution (cc)	Quantity of Fatty Acid (cc)	Gel Formation Yes	No	Gel Quality	Comments
100 (1)	100	x		Fair	Plug in simulated tank wall not removed.
100 (2)	100	x		Poor - not homogeneous	Plug in simulated tank wall not removed. Gel formed in bottom of tank only.
100 (3)	100	x		Poor - not homogeneous	Plug in simulated tank wall not removed. Gel formed in bottom of tank only.
125 (4)	100	x		Poor - not homogeneous	Plug in simulated tank wall not removed. Gel formed in bottom of tank only.
100 (5)	100	x		Poor - not homogeneous	Plug in simulated tank wall not removed. Gel formed in bottom of tank only.
100 (6)	100	x		Poor fluid	Plug in simulated tank wall not removed. Fatty acid injected 2 seconds prior to caustic solution.
100 (7)	100	x		Poor fluid	Plug in simulated tank wall not removed. Fatty acid injected 2 seconds prior to caustic solution.
100 (8)	100	x		Good firm	Plug in tank wall not removed. Caustic solution emulsified in JP-4. DMSO added to acid to increase reaction rate.

TABLE VI (Cont.)
FUEL TANK SEALING EXPERIMENTS USING GUEL GELATION REACTIONS - SIMULATED COMPARTMENTED TANK

Quantity of Caustic Solution (cc)	Quantity of Fatty Acid (cc)	Gel Formation Yes	Gel Formation No	Gel Quality	Comments
50 (9)	50		x	Good firm	DMSO added. Caustic solution emulsified. Plug in tank wall not removed.
100 (10)	100	x		Good firm	DMSO added. Caustic solution emulsified. Plug in tank wall not removed.
100 (11)	100	x		Good firm	DMSO added. Caustic solution emulsified. Plug in tank wall not removed.
100 (12)	100	x		Good firm	DMSO added. Caustic solution emulsified. Plug in tank wall not removed.
100 (13)	100	x		Good firm	DMSO added. Caustic solution emulsified. Plug in tank wall not removed.
100 (14)	100	x		Fair	DMSO added. Caustic solution emulsified. Plug in tank wall not removed. Aiming tubes directed at one another.
100 (15)	100	x		Good firm	Same as 14 except aiming tubes as follows: FA directed down side of compartment. C directed at center of compartment.
100 (16)	100	x		Poor fluid	Same as 14 except aiming tubes as follows: FA and C directed at front of compartment.
100 (17)	100	x		Poor fluid	Same as 14 except aiming tubes as follows: FA and C directed at front of compartment.

TABLE VI (Cont.)
FUEL TANK SEALING EXPERIMENTS USING FUEL GELATION REACTIONS - SIMULATED COMPARTMENTED TANK

Quantity of Caustic Solution (cc)	Quantity of Fatty Acid (cc)	Gel Formation Yes	Gel Formation No	Gel Quality	Comments
100 (18)	100	x		Poor fluid	Same as 14 except aiming tube as follows: FA and C directed at front of compartment.
100 (19)	100	x		Good firm	Same as 18. Plug in tube wall removed just prior to injecting agents. No seal was obtained.

APPENDIX II (U)

EXPERIMENTAL DATA, PREFORMED GELS AS FUEL TANK SEALANTS

CRYSTALLINE GELS AS FUEL TANK SEALANTS

The experimental data obtained on the sealing capability of crystalline gels are tabulated in Tables VII and VIII and discussed in the following paragraphs:

1. In Experiments 1 and 2, the distance between the fuel container walls was set at 1/4 inch. This system sealed a 9 mm entrance hole under a 3-foot head of fuel when the impact area was covered with a sheet of 1/16-inch rubber. The rubber served to decrease the size of the hole.

2. In order to seal the projectile exit hole more effectively, the distance between the walls of the fuel container was increased to 1/2 inch in subsequent experiments

3. Reproducible sealing of the entrance hole was accomplished only when rubber was used to decrease the size of the hole. Entrance hole seals were then accomplished under the fuel heads ranging from 1 to 3 feet. No exit hole seals were obtained.

4. Experiments 9 through 11 were performed to determine whether the formation of additional gel after projectile impact would have an effect on sealing the fuel container. Three to ten percent by weight of fatty acid was dissolved in the fuel and 100 to 400 percent by weight of excess caustic solution was added to the crystalline gel. There was no evidence to indicate that additional gel had been formed after projectile impact, and no improvement in sealing capability was experienced.

5. The gel containing 30 percent solids performed slightly better than the less concentrated material. However, reliable sealing capability was also demonstrated only in the experiments in which rubber sheet was employed to decrease the size of the projectile hole. The suspension of nylon fiber in the gel did not improve sealing performance. Impregnation of gel in a loosely woven cloth prevented sealing.

DILATANT GEL AS A FUEL TANK SEALANT

The data obtained on the sealing capability of the dilatant gel against 9 mm projectiles are shown in Table IX.

TABLE VII
CRYSTALLINE GEL CONTAINING
20 PERCENT SOLIDS, 9 MM BALLISTICS TESTS

Experiment	Gel Container Thickness (in.)	Fuel Head (ft.)	Seals Ent.	Seals Exit	Seals None	Comments
1	1/4	3	-	-	X	Rubber not used.
2	1/4	3	X	-	-	Impact point covered with thin sheet of rubber. Exit area also covered with rubber.
3	1/2	1	X	-	-	Rubber not used.
4	1/2	1	-	-	X	Rubber not used.
5	1/2	1	-	-	X	Rubber not used.
6	1/2	1	X	-	-	Impact point and exit area covered with thin sheet of rubber.
7	1/2	1	X	-	-	Impact point and exit area covered with thin sheet of rubber.
8	1/2	1	X	-	-	Impact point and exit area covered with thin sheet of rubber.
9	1/2	1	-	X	-	200% by wt. excess caustic solution in gel. 5% by wt. excess fatty acid in fuel.
10	1/2	1	-	-	X	400% by wt. excess caustic solution in gel. 10% by wt. excess fatty acid in fuel. Impact and exit points covered with rubber.
11	1/2	2	-	-	X	100% excess caustic solution. 5% excess fatty acid.
12	1/2	3	-	-	X	No additives in gel.
13	1/2	3	X	-	-	Impact point and exit area covered with thin sheet of rubber.
14	1/2	3	X	-	-	Impact point and exit area covered with thin sheet of rubber.

TABLE VII (Cont.)
CRYSTALLINE GEL CONTAINING
20 PERCENT SOLIDS, 9 MM BALLISTICS TESTS

Experiment	Gel Container Thickness (in.)	Fuel Head (ft.)	Seals Ent.	Seals Exit	Seals None	Comments
15	1/2	3	-	-	X	Impact point and exit area covered with thin sheet of rubber.
16	1/2	3	X	-	-	Impact point and exit area covered with thin sheet of rubber.

TABLE VIII
CRYSTALLINE GEL CONTAINING 30 PERCENT SOLIDS,
9 MM BALLISTICS TESTS

Experiment	Gel Container Thickness (in.)	Fuel Head (ft.)	Seals Both	Seals Ent.	Seals Exit	Seals None	Comments
17	1/2	1	-	X	-	-	Impact point and exit area covered with thin sheet of rubber.
18	1/2	1	-	X	-	-	Impact point and exit area covered with thin sheet of rubber.
19	1/2	1	X	-	-	-	Apparently projectile was not tumbled as it passed out of the tank.
20	1/2	2	-	-	-	X	Gel could not contain extra foot of fuel without using rubber over impact area.
21	1/2	2	-	X	-	-	Impact point and exit area covered with thin sheet of rubber.
22	1/2	2	-	X	-	-	Impact point and exit area covered with thin sheet of rubber.
23	1/2	2	-	X	-	-	Impact point and exit area covered with thin sheet of rubber.
24	1/2	2.5	-	X	-	-	1.5% by weight nylon fiber mixed into gel. Impact point and exit area covered by thin rubber sheet.
25	1/2	3	-	-	-	X	Gel could not contain 3-foot head of fuel without using rubber over impact area.
26	1/2	3	-	X	-	-	Impact point and exit area covered with rubber sheet.
27	1/2	3	-	-	-	X	Gel could not contain 3-foot head of fuel without using rubber over impact area.
28	1/2	3	-	X	-	-	1.5% nylon-fiber mixed into gel. Impact point and exit area covered with rubber sheet.

TABLE VIII (Cont.)
CRYSTALLINE GEL CONTAINING 30 PERCENT SOLIDS, 9 MM BALLISTICS TESTS

Experiment	Gel Container Thickness (in.)	Fuel Head (ft.)	Seals: Both	Seals: Ent.	Seals: Exit	Seals: None	Comments
29	1/2	3	-	X	-	-	1.5% nylon fiber mixed into gel. Impact point and exit area covered with rubber sheet.
30	1/2	3	-	X	-	-	2% nylon fiber mixed into gel.
31	1/2	3	-	X	-	-	2% nylon fiber mixed into gel. Impact point and exit area covered with thin sheet of rubber.
32	1/2	3	-	-	-	X	Gel impregnated on loosely woven cloth.
33	1/2	3	-	-	-	X	Gel impregnated on loosely woven cloth.

TABLE IX
DILATANT GEL - 9 MM BALLISTICS TESTS

Sealing System	Fuel Head (feet)	Seals		Comments
		Entrance	None	
1/2 interwall	1	-	x	Xylene, JP-4 solvent.
1/2 interwall Rubber outside	1	x	-	Xylene, JP-4 solvent.
1/2 interwall	3	x	-	Xylene, JP-4 solvent.
1/2 interwall	1	x	-	Xylene, DMSO solvent.
1/2 interwall	1	x	-	Xylene, JP-4 solvent.
1/2 interwall	3	x	-	Xylene, DMSO solvent.
1/2 interwall Rubber outside	2.5	x	-	Xylene, DMSO solvent.
1/2 interwall Rubber outside	1	x	-	Nylon fiber mixed into gel.
1/2 interwall Rubber outside	3	x	-	Nylon fiber mixed into gel.
1/2 interwall	3	x	-	Nylon fiber mixed into gel.
1/2 interwall	3	x	-	Nylon fiber mixed into gel.

APPENDIX III (C)

EXPERIMENTAL DATA, FOAMING REACTIONS FOR SEALING FUEL TANKS (U)

(U) DEVELOPMENT OF AN OPTIMUM FOAM FORMULATION

Tables X through XIII review the experiments performed to establish the optimum foaming formulations used in 9 mm and large-scale ballistics testing. Tables X through XII compare the reaction rates and foam quality of silicone, polyurea and polyurethane foams. Table XIII shows the effect of dimethyl sulfoxide and water on the curing and foaming rate of polyurethanes.

(C) 9 MM BALLISTICS TESTING (U)

Table XIV outlines the data obtained from the 9 mm ballistic testing of the polyurethane sealing material. The individual experiments are discussed in greater detail below.

1. In Experiments 1 through 5, the Pluracol EDP-500 solution containing catalyst, water and dimethyl sulfoxide was suspended in containers in the Hylene TM-65 which was between the fuel container walls. In all of these experiments, there was insufficent contact between the reactants, and not enough foam was produced for a seal.

2. In Experiments 6 through 19, triple-walled fuel containers were used in which equal quantities of Hylene TM-65 and Pluracol EDP-500 solution were contained separately between the walls. In each of these experiments, except for 6, 12, and 18, the Pluracol EDP-500 solution was placed at the outside of the fuel container so that it would be struck first by the entering projectile. In each of the three exceptions, when the Hylene TM-65 was placed at the outside of the fuel container, insufficient foam was produced for sealing.

3. Beginning with Experiment 8, tests were performed in an environment where ambient temperatures ranged between 35° and 45°F. This was the primary reason for failure to produce a seal in Experiments 8 through 13.

4. In Experiments 10 through 13, a new foaming formulation was used which was more reactive at reduced temperatures and produced more foam. This formulation is as follows:

40.5% by weight Pluracol EDP-500
35.4% by weight Hylene TM-65 (Toluene diisocyanate)
16.6% by weight Dimethyl sulfoxide
3.5% by weight Water
2.5% by weight Stannous Octoate
1.5% by weight Aniline

Although faster reactions and larger volumes of foam were obtained at reduced temperature with the new formulation, reliable sealing was not achieved by this alone. In Experiment 14, the innermost wall of the fuel container was coated with thin rubber sheet so as to restrict the flow of fuel into the reactants, thus reducing dilution. An entrance seal was achieved in this case.

5. In Experiments 15 and 16, the reactants were heated to 95°F prior to enclosing them between the tank walls. The reactions were violent and rapid, and seals were obtained in both cases.

6. In Experiments 17 through 19, the fuel containers were constructed with frangible partitions between the foaming agents. These partitions were shattered as the result of projectile impact creating a large area of contact between the reactants. The reaction was extremely rapid. Large quantities of foam were instantly produced, even at the cold temperatures (35°F).

TABLE X (U)
RELATIVE RATES OF SILICONE CURE USING
DOW CATALYST AND STANNOUS OCTOATE CATALYST

Silicone	Catalyst	Cure-Begin Time (sec)	Cure-Complete Time (min)
Elastomer	Dow amine	60	4
	Stannous octoate	30	2
Rigid Foam	Dow amine	5	4
	Stannous octoate	8	2
Flexible Foam	Dow amine	60	6
	Stannous octoate	20	1.5

TABLE XI (U)
POLYUREA FOAMS - REACTIONS OF VARIOUS AMINES WITH TOLUENE DIISOCYANATE

Amine	Wt. of Amine (grams)	Wt. of Isocyanate (grams)	Reaction Time in Seconds		Product Description
			Start	Finish	
Amine O+	4	4	6	10	Rigid foam
Amine T+	4	4	35	95	Semirigid foam
Amine C+	4	4	35	75	Semirigid foam
Alamine 34 ++	4	4	0	45	Crumbly foam
Duomeen 50 +++	4	4	60	120	Crumbly foam
Monamine AD 100++++	4	4	20	90	Rigid foam
Monamine AA 100++++	4	8	20	60	Rigid foam
Monamine AF 100++++	4	4	20	120	Semirigid foam
Ethylene-diamine	4	4	10	11	Powder
Amylamine	4	4	0	35	Loose gum - no foam
Morpholine	4	4	0	40	Powder

+ Product of Geigy Chemical Corporation, Ardsley, New York
++ Product of General Mills Corporation, Kankakee, Illinois
+++ Product of Armour and Company, Chicago, Illinois
++++ Product of Mona Industries, Inc., Patterson, New Jersey

TABLE XII (U)
POLYURETHANE FOAMS - REACTION OF TOLUENE DIISOCYANATE WITH VARIOUS POLYFUNCTIONAL ALCOHOLS

Polyol*	Reactants (%)		Reaction Time in Seconds		Product Description
	Mole Ratio	Catalyst	Start	Finish	
Pluracol TP 440	2.5:1	3.5	15	40	Rigid, slightly expanded foam
Pluracol Pep 450	2.5:1	3.5	15	35	Rigid, slightly expanded foam
Pluracol Pep 550	2.5:1	3.5	15	35	Hard, crumbly
Pluracol Pep 650	2.5:1	3.5	15	45	Spongy, slightly expanded foam
Pluracol P 410	2.5:1	3.5	15	-	No solid
Pluracol P 710	2.5:1	3.5	15	-	No solid
Pluracol TP 740	2.5:1	3.5	20	60	Rigid, slightly expanded foam
Pluracol SP 760	2.5:1	3.5	30	120	Soft gum
Pluracol EDP 500	2.5:1	3.5	12	30	Rigid, slightly expanded foam
Quadrol	2.5:1	3.5	25	55	Soft gum

* All products of Wyandotte Chemical Corporation, Wyandotte, Michigan

TABLE XIII (U)
EFFECT OF DIMETHYL SULFOXIDE AND WATER ON
REACTION OF PLURACOL EDP-500 AND TOLUENE DIISOCYANATE

Mole Ratio Diisocyanate to Polyol	Wt. % DMSO	% Catalyst	% H_2O	Reaction Time In Seconds		Product Description
				Start	Finish	
4:1	0	3.5	0	5	25	Slightly expanded foam
4:1	20	3.5	0	3	20	Slightly expanded foam
4:1	20	3.5	1	0	7	Greatly expanded foam

TABLE XIV (C)
POLYURETHANE FOAM SEALING MATERIAL - 9 MM BALLISTICS TESTING (U)

Experiment	Relative Location of Sealing Agent Between Tank Walls: Polyol	Relative Location of Sealing Agent Between Tank Walls: Isocyanate	Fuel Head (feet)	Spacing Between Walls (inches)	Seals: Both	Seals: Ent.	Seals: Exit	Seals: None	Comments
1	Inside rubber pouch attached to outside tank wall	Between tank walls	1	1/2	-	-	-	x	Inadequate foam. Insufficient contact between reactants.
2	Plastic bags suspended in isocyanate	Between tank walls	1	1/2	-	-	-	x	Inadequate form. Insufficient contacts between reactants.
3	Plastic bags suspended in isocyanate	Between tank walls	1	1/2	-	-	-	x	Inadequate foam. Insufficient contact between reactants.
4	Double layer of bags suspended in isocyanate	Between tank walls	1	1/2	-	-	-	x	Inadequate foam. Insufficient contact between reactants.
5	In plastic tanks suspended in isocyanate	Between tank walls	1	1/2	-	-	-	x	Inadequate foam. Insufficient contact between reactants.
6	Inside	Outside	1	1/2	-	-	-	x	Much foam outside of tank. Not enough reaction at point of projectile impact.
7	Outside	Inside	1	1/2	-	x	-	-	Much foam outside of container at exit side. Very good and rapid entrance seal.

TABLE XIV (Cont.) (C)
POLYURETHANE FOAM SEALING MATERIAL - 9 MM BALLISTICS TESTING (U)

Experiment	Relative Location of Sealing Agent Between Tank Walls		Fuel Head (feet)	Spacing Between Walls (inches)	Seals				Comments
	Polyol	Isocyanate			Both	Ent.	Exit	None	
8	Outside	Inside	1	1/2	-	-	-	x	Test environment about 39°F. Very little reaction.
9	Outside	Inside	1	1/2	-	-	-	x	Test environment about 39°F. Very little reaction.
10	Outside	Inside	1	1/2	-	-	x	-	New formulation. Increases water concentration.
11	Outside	Inside	1	1/2	-	-	-	x	New formulation. Reaction sluggish.
12	Inside	Outside	1	1/2	-	-	-	x	New formulation. Reaction sluggish. No provision for sealing exit.
13	Inside	Outside	1	1/2	-	-	-	x	New formulation reaction faster. No provision for exit sealing.
14	Outside	Inside	1	1/2	-	x	-	-	Rubber placed between reactants and fuel. No provision for exit sealing.
15	Outside	Inside	1	1/2	-	x	-	-	Original formulation. Reactants heated to 95°F. No provision for exit sealing.

TABLE XIV (Cont.) (C)
POLYURETHANE FOAM SEALING MATERIAL - 9 MM BALLISTICS TESTING (U)

Experiment	Relative Location of Sealing Agent Between Tank Walls		Fuel Head (feet)	Spacing Between Walls (inches)	Seal				Comments
	Polyol	Isocyanate			Both	Ent.	Exit	None	
16	Outside	Inside	3	1/2	-	x	-	-	Original formulation. Reactants heated to 95°F Partial seal only. No exit sealing provision.
17	Outside	Inside	3	1/2	-	x	-	-	Original formulation. Temperature 35°F. Frangible middle wall. No provision for exit sealing.
18	Inside	Outside	3	1/2	-	-	-	x	Original formulation. Temperature 35°F. Frangible middle wall. Foam increased. No provision for exit sealing.
19	Outside	Inside	3	1/2	-	x	-	-	Original formulation. Temperature 35°F. Frangible middle wall. Partial seal only. No provision for exit sealing.

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13. ABSTRACT

Rapid gelation reactions, rapid foam-forming reactions and preformed gels have been studied as sealing materials for self-sealing fuel tanks. The rapid gelation reactions were found not to be feasible sealing materials.

Rapid foam-forming reactions and some preformed gel formulations containing high concentrations of solids are feasible fuel tank sealants.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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